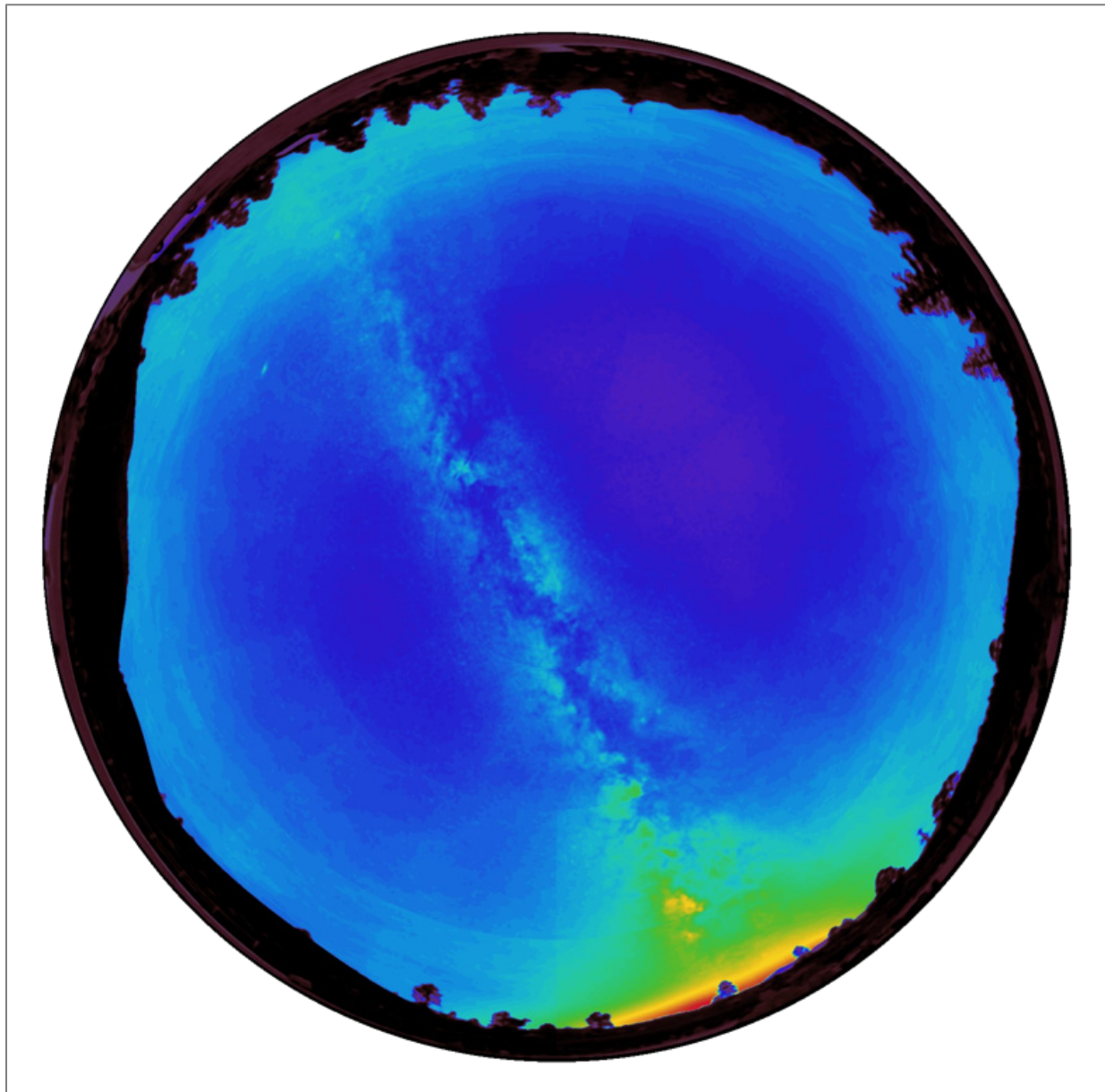




Night Skies Data Report

Photometric Assessment of Night Sky Quality at Sunset Crater Volcano National Monument



Fisheye view of the night sky over Sunset Crater Volcano National Monument in false color.
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Night Skies Data Report: Photometric Assessment of Night Sky Quality at Sunset Crater Volcano National Monument

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Tyra A. Olstad , Li-Wei Hung, Erik Meyer 

National Park Service
Natural Resource Stewardship and Science
Natural Sounds and Night Skies Division
Fort Collins, Colorado

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Abstract

This report characterizes night sky conditions in Sunset Crater Volcano National Monument (SUCR) 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 one site. These ground-based observations were collected on seven nights between June 20, 2004, and March 13, 2012. Satellite data from 2023 were used to create a map of predicted night sky conditions in and around the park.

The sky overhead remains fairly dark with an average zenith brightness of 21.67 magnitudes per square arcsecond (mag/arcsec^2), close to the darkest level expected for pristine night skies, 22.0 mag/arcsec^2 . We estimate that 92.4–97.1% of naked eye stars were visible throughout the data collection period, providing a good opportunity to view the natural night sky from the park during a cloudless moonless night. The whole sky over SUCR is 10%–21% (mean = 17%) brighter than average natural levels, indicating very good dark sky conditions on average.

In SUCR, we classified the sky as Bortle Class 3 (rural sky), based on the visibility of astronomical objects. The average naked eye limiting magnitude (NELM) is 6.8–7, which indicates a very dark night sky with excellent viewing conditions. Light pollution is present along the south-southwestern horizon, but the sky zenith is relatively unimpacted. The Milky Way is visible horizon to horizon with a high level of detail. The main impacts on SUCR's night sky quality are light domes from Flagstaff, Phoenix, and their surrounding communities.

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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 equals 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 of 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 falling 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 the 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 essential component of natural and cultural environments. Although intangible, it is an important natural, cultural, educational, and economic resource. It affords 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 influenced numerous cultures around the globe. Today, star parties attract many visitors to parks, 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 offered, providing unique educational opportunities and immersive experiences.

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.”

In collaboration with NPS regions, parks, and programs, the Natural Sounds and Night Skies Division (NSNSD) provides service-wide 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 former provide accurate measurements of the night sky as experienced by wildlife and park visitors, while the latter measures the upward radiance of the nighttime earth, providing a regional perspective of the lights that are altering the night sky. 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. We discuss the natural brightness variation, measurement uncertainties, glare, and trend analysis limitations in the Discussion chapter. 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 links to 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). Skyglow is light from anthropogenic sources that is scattered by or reflected off air molecules and atmospheric aerosols, brightening the sky and washing out celestial objects. 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.

Sunset Crater Volcano National Monument (SUCR) is located about 15–20 miles north-northeast of Flagstaff, in central Northern Arizona (Figure 1). It was established in 1930 to protect Sunset Crater itself—the least-eroded cinder cone in the San Francisco Volcanic Field—as well as surrounding lava flows, lava tubes, cinder cones, and pockets of vegetation nestling amid the volcanic features, filling a total of 3,040 acres. Having last erupted about 900 years ago, Sunset Crater also features in local archaeology and ethnography, representing “the only series of eruptions in the Southwest indisputably witnessed by local peoples” (NPS 2015, p. 3). The last eruption forced Ancestral Puebloan people who had lived near the volcano to relocate to nearby communities, including Walnut Canyon and Wupatki—now, neighboring National Monuments.

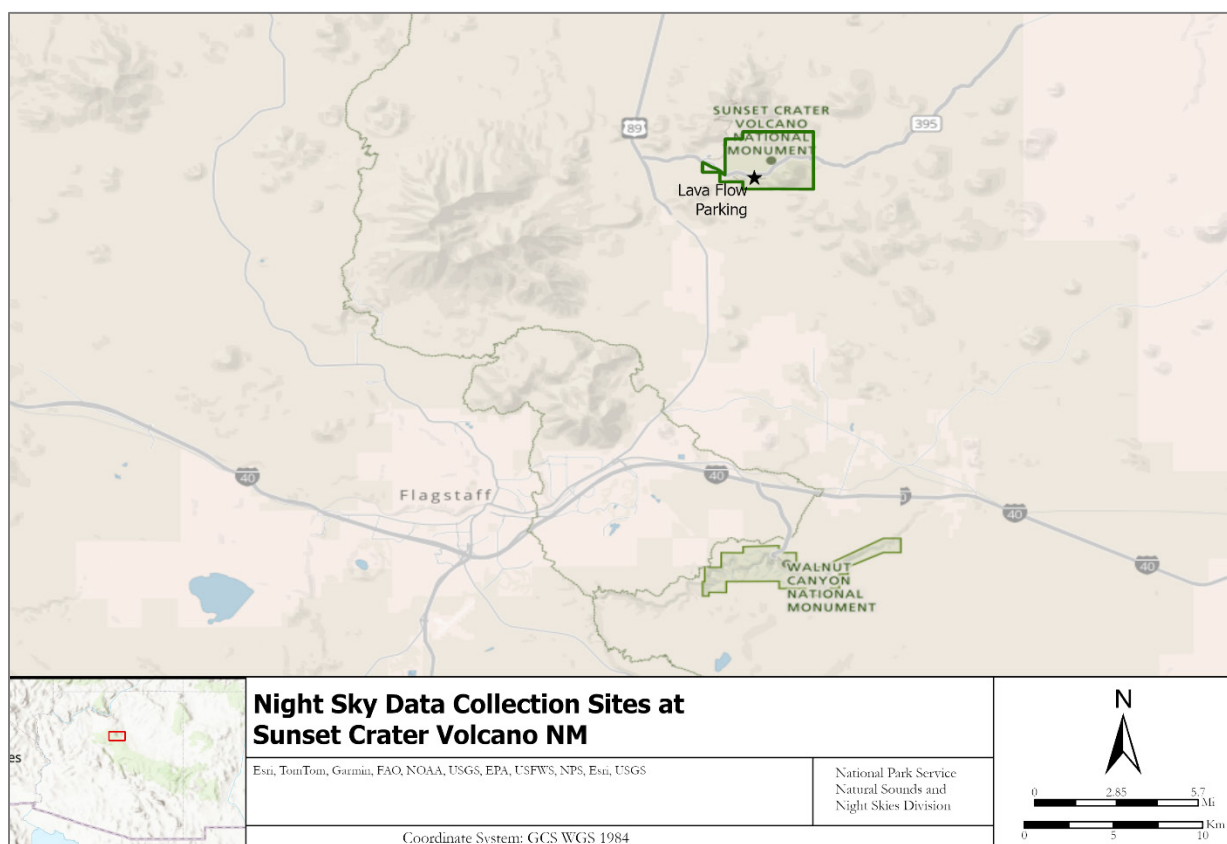


Figure 1. Geographic location of the park, including the night skies data collection site. Sunset Crater Volcano National Monument is located about 15–20 miles north of Flagstaff in central northern Arizona, between Wupatki National Monument (off the map, to the north) and Walnut Canyon National Monument. In general, light sources within 300 km could be visible and have the potential to brighten the night sky.
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The dramatic landscape and scenery are one of the park’s fundamental resources and values, occurring “within an environment of clean air and pristine night skies,” according to the Foundation Document (NPS 2015, p. 6). However, the park’s clean air and views of starry skies may be

threatened by emerging wildfire regimes. In 2022, the Tunnel Fire burned through surrounding pinyon and ponderosa stands on Coconino National Forest, also damaging roads and infrastructure.

Along with nearby Wupatki and Walnut Canyon National Monuments (all together referred to as the Flagstaff Area Monuments), Sunset Crater received certification as an International Dark Sky Park in 2016.

Contributing to night sky quality and Dark Sky Park certification: the closest major city, Flagstaff, is the world's first International Dark Sky City, certified as such in 2001. Home to Lowell Observatory, Flagstaff's strict lighting codes dramatically reduce light pollution. According to the Flagstaff Dark Skies Coalition, Flagstaff's "sky glow has been measured as more than 90% less than other towns of similar size."

Phoenix, located about 138 miles (250 km) south, has made efforts to convert LED streetlights to fixtures with color temperature 2700K (City of Phoenix 2024). This aligns with many dark sky friendly lighting guides, such as DarkSky International's requirement that DarkSky approved luminaires have a maximum color temperature of 3,000K (DarkSky International 2025).

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 be somewhere between 8 and 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.

Between June 20, 2004, and March 13, 2012, NSNSD collected 7 nights of ground-based CCD camera data in SUCR, yielding 16 complete data sets (Table 1). Each set is used to generate a panoramic image of the night sky. When able to collect multiple data sets in a night, we analyze the highest quality one.



Figure 2. 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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Table 1. Ground-based data collection events at Sunset Crater Volcano 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
6/20/2004	Lava Flow Parking	SBIG 1	5	D Duriscoe
2/9/2005	Lava Flow Parking	SBIG 1	2	D Duriscoe; R Stark
3/1/2005	Lava Flow Parking	MaxCam 1	1	C Moore; R Stark
3/12/2005	Lava Flow Parking	MaxCam 1	1	C Moore; A Richman; C Luginbuhl
2/24/2006	Lava Flow Parking	IMG 1	1	C Moore
9/18/2006	Lava Flow Parking	IMG 1	2	C Moore
3/13/2012	Lava Flow Parking	IMG 2	4	J White; C Leumas

Locating Data Collection Sites

NSNSD carries out observations with the CCD camera at carefully chosen 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 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 or park with an irregular boundary, multiple sites are used to capture the range of sky quality across the park (Table 2 and Figure 1).

Table 2. Data collection site at Sunset Crater Volcano National Monument.

Site Name	Elevation (m)	Latitude	Longitude
Lava Flow Parking	2,124.143	35.36257	-111.5187

Lava Flow Parking

The Lava Flow parking area is one of the main stopping points in Sunset Crater Volcano National Monument, providing access to two trails, a picnic area, and an amphitheater. It’s located about 1.5 miles from the park Visitor Center and Bonito Campground. As NSNSD staff noted, its accessibility and open views make it a good site for telescopes and public night sky viewing, despite potential traffic (and headlights) on the Loop Road. Although silhouettes of hills, trees, and Sunset Crater itself block some of the horizon, light domes from Phoenix and Flagstaff are visible to the south and southwest. Uniquely, the blackness of the surrounding basalt accentuates the depth of the night sky, enhancing the overall effect of darkness.

Processing Night Sky Images

For each data set, NSNSD processes 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 seven 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. The Dark Sky Association 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 onboard 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. The DNB has a swath width of 3,000 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. Figures 3–5 are examples from March 13, 2012, and September 18, 2006. Appendix A: Observation Notes and Panoramic Images provides links to a complete gallery of the reference images for each site each night.

Each panorama depicts sky surface brightness in units of magnitude per square arcsecond ($\text{mag}/\text{arcsec}^2$), a standard unit for measuring the brightness of astronomical objects. The values are in an inverted logarithmic scale: under clear moonless conditions, a sky surface brightness of 22 $\text{mag}/\text{arcsec}^2$ would be considered pristine; a sky surface brightness of $<20 \text{ mag}/\text{arcsec}^2$ would be considered greatly deviated from the natural condition. A difference of 5 magnitudes corresponds to a 100-times difference in brightness. The images are shown in false color, with warmer colors depicting lower values, representing 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, with the natural condition of the Milky Way appearing light green. 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. In the image, lights from Flagstaff and suburbs blend together with light from Phoenix and surrounding cities to create the largest and brightest cluster of light domes, stretching from about 190° – 220° south-southwest and extending about 20° upward into the sky. Although hills shield some light along the southeastern horizon, skyglow persists from the main light dome to about 120° , encompassing Twin Arrows as well as Winslow. The remainder of the horizon and night sky remain remarkably pristine.

Of note, the Estimated Artificial Sky Brightness Mosaic derived from images taken at the Lava Flow Parking site on September 18, 2006, reveals a very prominent light dome to the northwest, at about 320° . These lights, which were not visible during the previous night sky data collection seven months earlier and were no longer present during the next night sky data collection period in 2012, appeared to be a very bright but temporary campsite or mining operation at the base of O’Leary Peak on Coconino National Forest or an inholding. As noted by NSNSD personnel, “[t]he impact is quite striking.”

Table 3 lists census-designated places nearby to the Lava Flow Parking site, 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. Moreover, Timberline-Fernwood, Doney Park, Mountain View Ranches, and Kachina Village blend into the lights of Flagstaff, while Mesa, Scottsdale, Peoria, and Glendale are part of the greater Phoenix metropolitan area. Also, as the world’s first International Dark Sky City, Flagstaff makes concerted efforts to limit light pollution, thus has a lower skyglow impact than would be predicted for a city of its size.

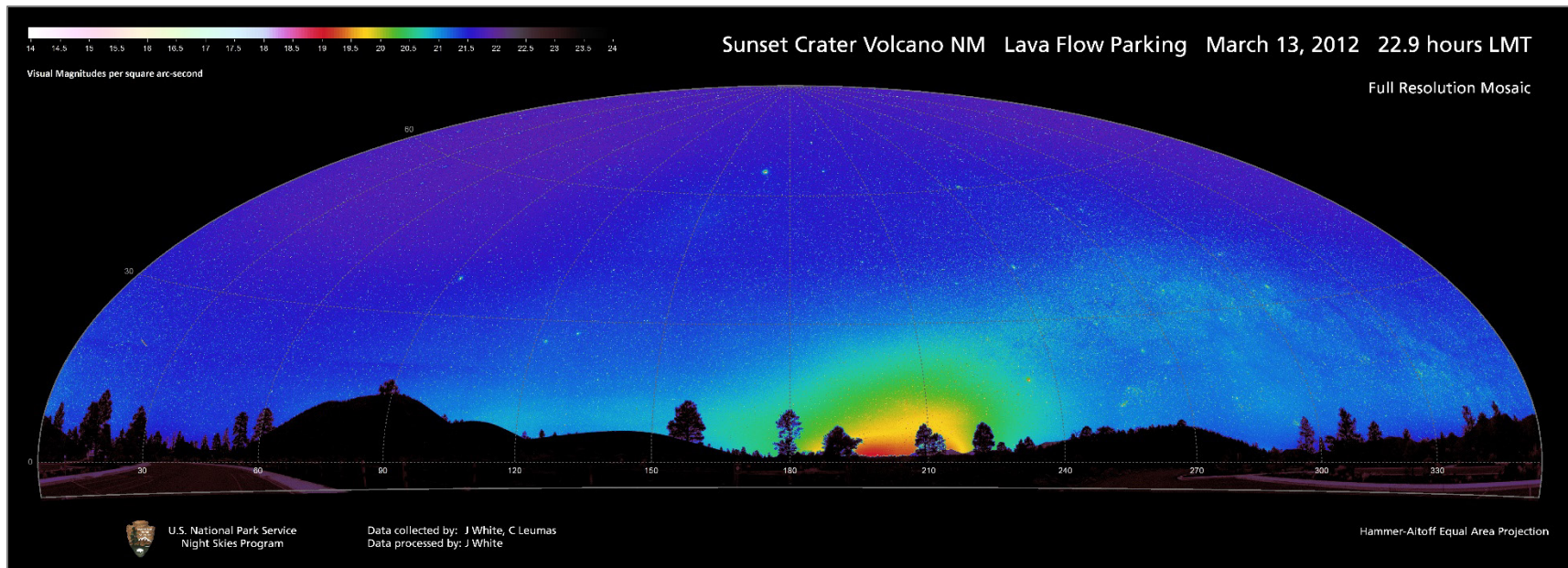


Figure 3. Panoramic image of the night sky from the Lava Flow Parking site on March 13, 2012. The observed sky shows light from all sources, both natural and artificial.

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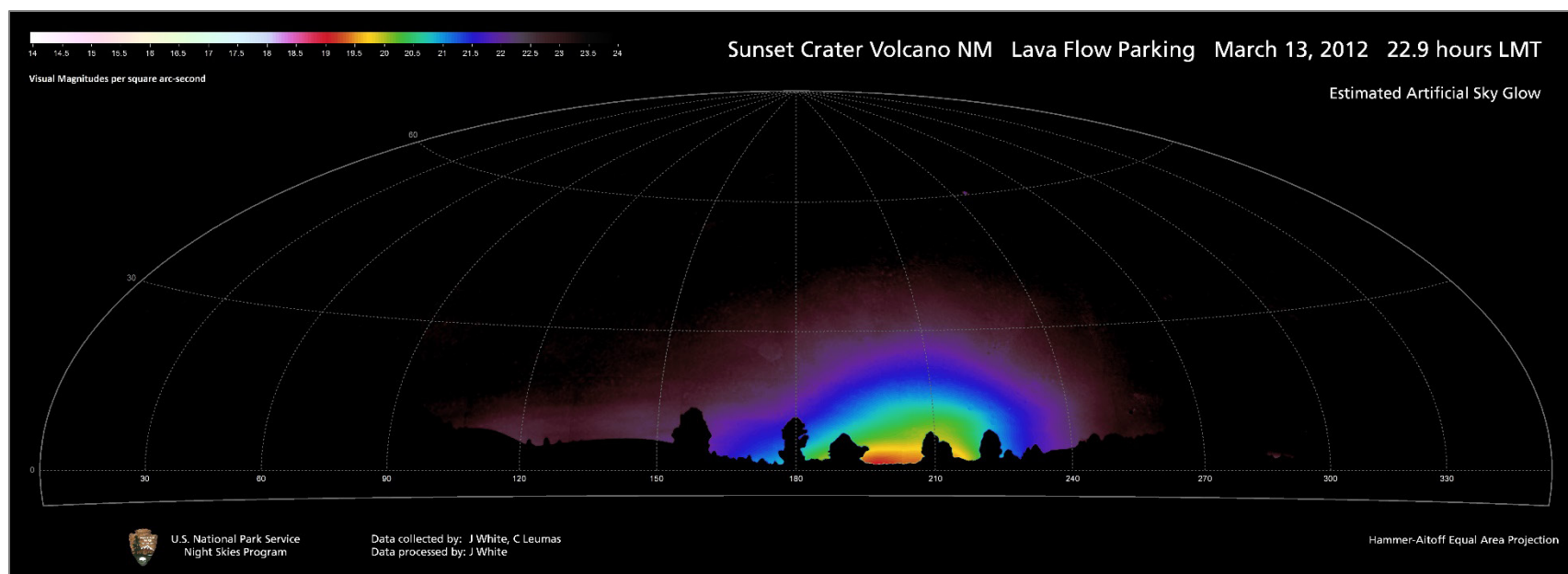


Figure 4. Panoramic image of artificial skyglow at the Lava Flow Parking site on March 13, 2012. Natural light has been removed from this image, showing only artificial skyglow and associated light domes.

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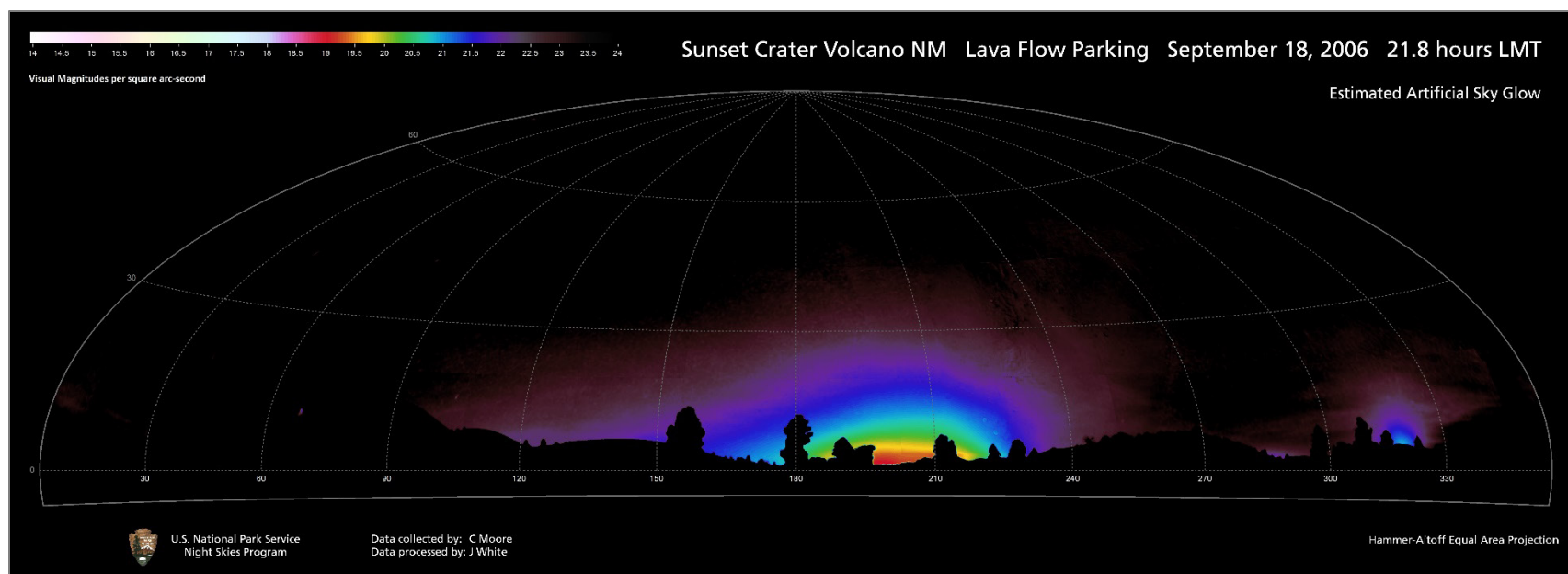


Figure 5. Panoramic image of artificial skyglow at the Lava Flow Parking site on September 18, 2006. The natural light has been removed from this image, showing only the artificial skyglow and associated light domes.

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Table 3. Nearby census-designated places and their predicted skyglow impact at the Lava Flow Parking site.

Place	Population in 2020	Distance (km)	Azimuth (degree)	Walker's Value (% above natural)
Timberline-Fernwood	2,572	6	210	29.17
Flagstaff	76,831	24	214	27.23
Doney Park	5,910	11	180	14.73
Phoenix	1,608,139	206	195	2.64
Mountain View Ranches	1,508	15	164	1.73
Fort Valley	1,682	21	238	0.83
Mesa	504,258	217	187	0.73
Scottsdale	241,361	189	190	0.49
Peoria	190,985	185	204	0.41
Kachina Village	2,502	34	208	0.37
Glendale	248,325	214	198	0.37

Sky Quality Indicators

Tables 4 and 5 summarize sky quality metrics at SUCR, including measurements derived from the CCD camera images and additional on-site measurements and visual observations.

Table 4. Sunset Crater Volcano National Monument sky brightness metrics derived from the observed images.

Site Name	Date	Time (hh:mm)	Horizontal Illuminance (mlx)	Max. Vertical Illuminance (mlx)	Zenith Luminance (mag/arcsec ²)	Stars Visible (%)	All-sky Light Pollution Ratio
Lava Flow Parking	6/20/2004	01:32	1.03	0.70	21.14	92.4	0.20
Lava Flow Parking	2/9/2005	00:01	0.75	0.60	21.89	92.7	0.21
Lava Flow Parking	3/1/2005	N/A	1.00	0.68	21.58	95.4	0.13
Lava Flow Parking	3/12/2005	22:43	1.03	0.71	21.63	97.1	0.10
Lava Flow Parking	2/24/2006	23:32	0.71	0.52	22.00	93.5	0.16
Lava Flow Parking	9/18/2006	21:47	0.93	0.67	21.68	96.9	0.20
Lava Flow Parking	3/13/2012	22:56	0.88	0.65	21.78	94.9	0.18
Rock Creek Park, Washington, DC	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. Sunset Crater Volcano National Monument visual and SQM measurements.

Site Name	Date	Bortle Class	Limiting Magnitude	SQM (mag/arcsec ²)
Lava Flow Parking	6/20/2004	3	6.8	–
Lava Flow Parking	2/9/2005	3	6.8	–
Lava Flow Parking	3/1/2005	–	–	–
Lava Flow Parking	3/12/2005	–	–	–
Lava Flow Parking	2/24/2006	3	7	–
Lava Flow Parking	9/18/2006	3	7	–
Lava Flow Parking	3/13/2012	3	6.8	21.77
Rock Creek Park, Washington, DC	Urban Sky ^A	8	5.2	18.36
–	Natural Sky ^B	1	7	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.

Metrics Derived from CCD Camera Images

Using the panoramic images taken at each site, we report five indicators (Duriscoe, 2016) that focus on different aspects of sky brightness: horizontal illuminance, maximum vertical illuminance, zenith brightness, percentage of stars visible, and all-sky light pollution ratio (ALR) (Table 4). If multiple data sets were taken in a single 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.

Illuminance is the amount of visible light incident on a unit surface area, measured in units of millilux (mlx). 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.

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 seven observation nights in SUCR, the average horizontal illuminance is only slightly higher than the natural reference, depending on each night's viewing conditions, indicating the park preserves to a large extent the natural illumination on the plane.

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 seven observation nights in SUCR, the maximum vertical illuminance from all sources is 0.71 mlx, and all observations are greater than the referenced natural value of 0.40 mlx. This shows how artificial lights measurably brighten the night sky along the horizon. Nonetheless, the overall illuminance level is still fairly low, indicating that the nighttime darkness is not overwhelmed by anthropogenic light.

Zenith sky brightness is the sky brightness measured within a 1-square degree area directly overhead. Because light domes are located along the horizon, the zenith usually is the darkest part of the sky. For reference, the darkest natural sky can reach V-band (visual band) brightness of 22 mag/arcsec², and the brightest part of the Milky Way is about 20 mag/arcsec². Overall, the photometric measurements in SUCR show the zenith is nearly pristine, with an average zenith brightness of 21.67 mag/arcsec². Any skyglow at zenith is so faint as to be immeasurable by our camera system.

On average, there are about 4,000 stars visible to the naked eye under the natural dark sky. *Percentage of stars visible* estimates how many of these stars are visible after accounting for the influence of skyglow. When calculating this metric, we take 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. This metric estimates the direct impact of skyglow to human visual observation of stars and night sky features. From the seven observation nights in SUCR, we estimate that on average, 94.7% of stars were still visible during data collection, providing an excellent opportunity to observe the natural night sky.

Lastly, *All-sky Light pollution Ratio* (ALR) is an index of total skyglow. We calculate it by dividing the total brightness due to skyglow by the brightness of the natural dark sky, in terms of a constant value of 250 microcandela per square meter. 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 SUCR is 10%–21% (mean = 17%) brighter than average natural levels, indicating excellent dark sky conditions.

Additional On-Site Measurements and Observations

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). A description for each of these metrics is provided below.

Developed by amateur astronomer John Bortle to help standardize comparisons of night sky brightness, *Bortle Class* is a widely used nine-level numeric scale that measures the brightness of a particular location based on visible sky objects (Bortle, 2001). A pristine night sky completely free of skyglow would rate as Class 1, while Class 9 indicates a heavily light-polluted sky, such as is often found over large cities. In SUCR, we rated skies as Bortle Class 3: Rural sky. As described by Bortle (2001, pp. 127–128):

“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.”

Naked eye limiting magnitude (NELM)—the magnitude of the faintest star we can see in the sky with naked eyes—is also a common metric used by citizen scientists to assess the sky brightness globally. 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. In SUCR, observations by NSNSD personnel identified stars with a limiting magnitude of up to 7.0—very faint astronomical features, requiring extraordinarily dark night skies and proper dark adaptation of the eye to see.

The hand-held *Sky Quality Meter* (SQM) is an economic and convenient tool to use to take a single value of sky brightness measurement with just one click. We point SQM devices towards zenith when taking a reading. The SQM has a wide field of view, with a full width half maximum of the angular sensitivity of $\sim 42^\circ$. Although getting a reading is fast and easy, the instrument does not reliably measure the sky brightness when the sky is darker than $\sim 21.5 \text{ mag/arcsec}^2$. Our lone SQM measurement in SUCR was $21.77 \text{ mag/arcsec}^2$, which is darker than what we can accurately measure with an SQM, but consistent with the zenith limiting magnitude measured from CCD images.

Regional Sky Brightness Model

Figure 6 displays park and regional predictions of skyglow based on the SALR model. The metric depicted is all-sky average sky brightness, expressed as a ratio of artificial to natural background. The color scale gives the ratio between the natural and artificial light where the lower the ratio, the better the night sky viewing and lower levels of visible artificial light. As skyglow can be seen from up to 300 kilometers away from large metropolitan areas, this map provides a landscape view of the average sky brightness in and around the park.

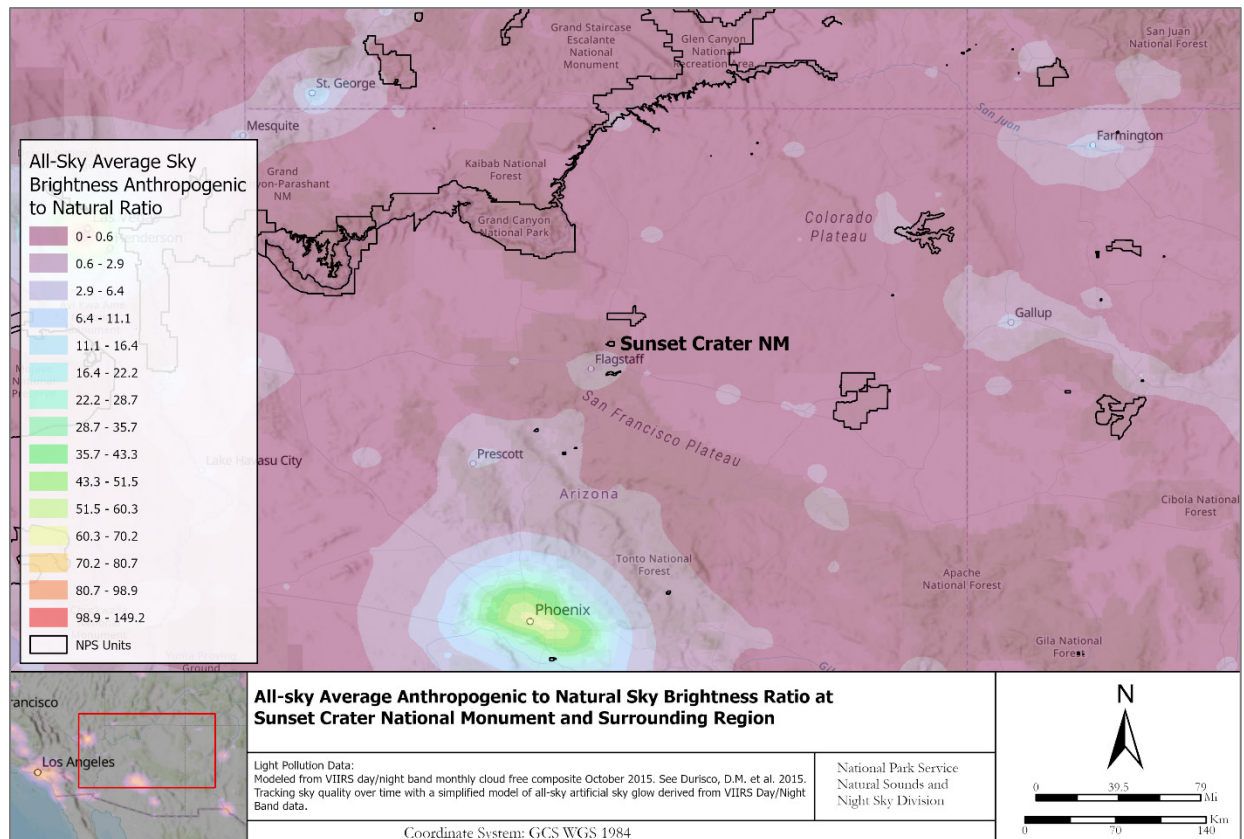


Figure 6. A model of average all-sky light pollution ratio (ALR) in the region surrounding Sunset Crater Volcano National Monument.

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While there are light sources near SUCR, most are far enough away to minimize impacts on the park's night skies. According to the model, Flagstaff, Tuba City, and Winslow are only minimally bright, with Prescott the closest moderately bright location and Phoenix the only major—but distant—source of light pollution. The model predicts that the mean ALR in the park is 0.33 (0.29–0.38)—more than double that of WUPA to the north. At this level, artificial light is beginning to increase nighttime brightness well beyond natural conditions, though humans should still have an opportunity to see the Milky Way and complete constellations.

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 (e.g., percent 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

Direct measurements have uncertainties of about a few percent, while 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). The all-sky average measurement of skyglow, such as ALR, is typically accurate to $\pm 5\%$, or 0.05 magnitudes.

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 miles, glare can significantly degrade the view of the night sky and impair an observer's night adapted vision. NSNSD staff observed very little glare from the Lava Flow Parking area.

Trend Analysis Limitations

Our analysis is focused on current conditions, not any long-term trends. Ground-based observations are limited by the sporadic and small number of sampling points in time. Some activities may increase or decrease otherwise constant light pollution dramatically, but only temporarily. For example, lights from a temporary campsite or mining operation had a striking impact on night sky quality in September 2006 (Figure 5) but weren't present 7 months earlier and were gone again by the next data collection period in 2012. Their presence in a single data set from a single site couldn't be used to evaluate permanent changes or trends. In addition, because each observation is taken under slightly different atmospheric conditions, the measurements cannot be directly compared. That said, these measurements do accurately reflect the sky quality at those specific points in 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 the actual lighting level change. Until this variation is well understood, we cannot use the satellite data to identify the trend.

Conclusions

Overall, the night sky conditions at SUCR are very good. The measured sky brightness averaged over the whole sky is only somewhat brighter than the natural conditions, allowing wildlife and park visitors to experience near natural darkness at night. Visitors can find places within the park free of direct glare, allowing for dark adaptation and night sky viewing under an almost natural sky. During clear and dark nights, visitors will have an opportunity to see the Milky Way, complete constellations, deep sky objects, and fainter natural sources of light such as the zodiacal light and airglow.

In SUCR, night skies were visually classified as rural (Bortle Class 3), based on the visibility of astronomical objects. Depending on atmospheric conditions, the NELM can reach as dim as is achievable to see under good conditions and with proper dark adaptation of the eye. Light pollution is, however, quite evident and can impact dark adaptation. A composite light dome from Flagstaff, Phoenix, and their surrounding communities is visible for 30° along and up to 20° above the horizon. While impacts from these light domes are moderate to low during clear nights, an increase in atmospheric aerosols can significantly alter sky brightness by amplifying the impacts of existing artificial light and further degrading the night sky quality. Moreover, local activities such as mining operations or camping on nearby land can temporarily but significantly increase light pollution along the horizon.

Practicing sustainable outdoor lighting within the park is key to reducing light pollution (NSNSD 2025). Sustainable outdoor lighting observes the following principles:

- light only if needed
- light only when needed
- light only where needed
- use recessed and fully shielded fixtures
- integrate timers and sensors
- use warm-white or amber light
- use the minimum amount of light needed
- and use energy-efficient light

Using appropriate lighting in the park can provide visitors the optimal observing environment. 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. As an International Dark Sky City, Flagstaff is a premier example of a gateway community that strives to mitigate light pollution. Doing so improves the quality of night sky viewing, which can, in turn, result in increased visitor spending in gateway communities. Preserving the natural night sky requires a joint effort and can be mutually beneficial to all parties.

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Appendix A: Observation Notes and Panoramic Images

6/20/2004, Lava Flow Parking

Site on southwest edge of Lava Flow Trail parking lot, on sidewalk. Horizons blocked somewhat by hills and a few trees, east blocked by Sunset Crater. Seeing good, transparency very good, very dark at zenith, lots of detail in Milky Way, two dark lanes seen northeast of Antares. Pretty good site for public or telescopes, though close to public road open all night. Light domes from Phoenix and Flagstaff merge to south-southwest, extend about 20 degrees above horizon. Sky is accentuated by blackness of surrounding land (cinders).

- Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/SUCR040620_hmrFULL.jpg
- Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/SUCR040620_hmrART.jpg

2/9/2005, Lava Flow Parking

Very damp, frost forming in early morning, very dark, clear. Seeing very good; transparency very good. Very dark at zenith, gegenschein visible easily, light dome from Flagstaff/Phoenix extends to 20 degrees above horizon SW, somewhat annoying to night vision but not too bad. Seems like airglow subdued tonight.

- Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/SUCR050209_hmrFULL.jpg
- Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/SUCR050209_hmrART.jpg

3/1/2005, Lava Flow Parking

- Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/SUCR050302_hmrFULL.jpg
- Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/SUCR050302_hmrART.jpg

3/12/2005, Lava Flow Parking

- Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/SUCR050313_hmrFULL.jpg
- Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/SUCR050313_hmrART.jpg

2/24/2006, Lava Flow Parking

Clear, transparent, stable. good night

- Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/SUCR060225_hmrFULL.jpg
- Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/SUCR060225_hmrART.jpg

9/18/2006, Lava Flow Parking

Good transparency but visible brightening around horizon- possibly faint airglow. Milky Way stretching across zenith, so total sky brightness will be elevated. New lights to NW. This appears to be a temporary logging operation, mining operation, or camp at the base of O'Leary Peak. The impact is quite striking.

- Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/SUCR060919_hmrFULL.jpg
- Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/SUCR060919_hmrART.jpg

3/13/2012, Lava Flow Parking

Sky was fairly bright with Mars, Venus, and Jupiter all up. Milky Way band was visible but very fine details were not visible towards the Flagstaff lightdome. More detail overhead and to the north. Uniform darkness at Zenith down to ZA30. Bright Airglow visible, especially silhouetted against Sunset Crater. SQM of 21.77 and SQM-L 21.67. No Clouds by the time we got to SUCR from WACA. Transparency very good, seeing was fair.

- Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/SUCR120314_hmrFULL.jpg
- Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/SUCR120314_hmrART.jpg

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1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525