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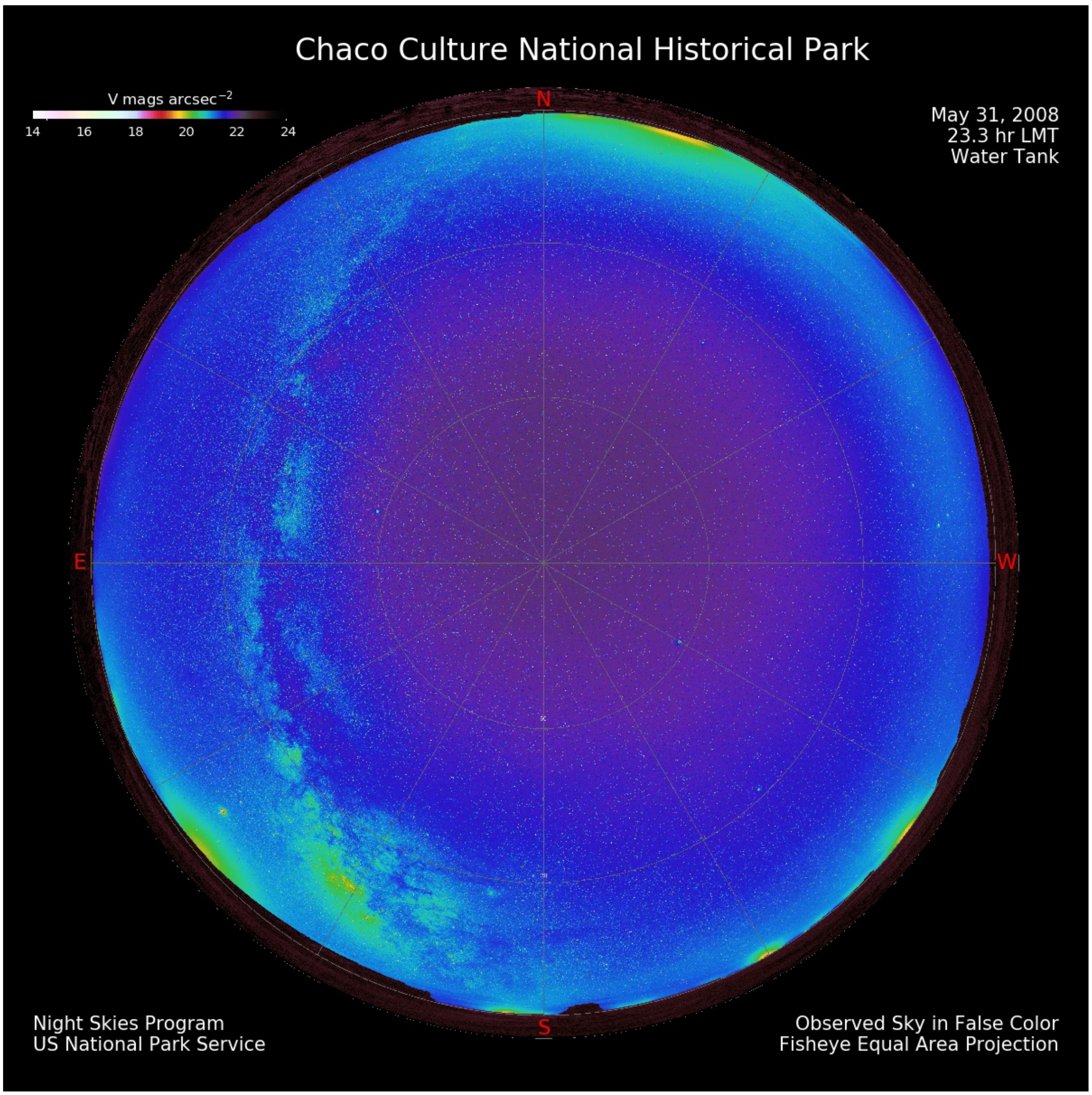
Natural Resource Stewardship and Science

Night Skies Data Report

Photometric Assessment of Night Sky Quality
Chaco Culture National Historical Park

Natural Resource Report NPS/NRSS/NSNSD/NRR—2019/1914



ON THIS PAGE

The Night Skies Team with Chaco staff assessing the monitoring location of Gallo Cuesta

Photograph courtesy of Jeremy White

ON THE COVER

Fisheye view of the night sky over Chaco Culture National Historical Park in false color

Photograph courtesy of the National Park Service Night Skies Program

Night Skies Data Report

Photometric Assessment of Night Sky Quality
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Natural Resource Report NPS/NRSS/NSNSD/NRR—2019/1914

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Executive Summary

Entrance to Chaco Culture National Historical Park with the Milky Way overhead.

This report characterizes night sky conditions in Chaco Culture National Historic Park 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 four sites. These ground observations were collected on nine nights from 2001 to 2016. Satellite data collected in 2016 was used to create a map of predicted night sky conditions in and around the park.

Overall, the photometric measurements demonstrate the night sky quality at Chaco Culture NHP is excellent. The average horizontal illuminance indicates the park preserves to a large extent of the natural illumination on the plain. Although the artificial lights have a measurable effect in brightening the night sky along the horizon, the maximum vertical illuminance from all sources is less than one mlx (about one tenth of a quarter moon). The low illuminance level provides a refuge for crepuscular and nocturnal species in the park. The sky overhead remains pristine with the average zenith brightness of 21.9 mag/arcsec^2. We estimate more than 90% of stars were still visible for the most of the time, providing an outstanding opportunity to observe the natural night sky from the park. Excluding the observation taken in 2014 under hazy conditions, the whole sky over Chaco Culture NHP is only 12-19% brighter than average natural levels, indicating excellent dark sky conditions.

The visual observations also suggest the darkest part of the sky remains pristine, and the whole sky is only slightly brighter than the natural conditions. In Chaco Culture NHP, 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 7.0, approaching the sensitivity limit of human eyes under good atmospheric conditions. Our SQM measurements average to 21.6 mag/arcsec^2, indicating the zenith is darker than what we can accurately measure with a SQM. From most locations within the park, visitors can find places free of direct glare and allow their eyes to be fully dark-adapted. During clear and dark nights, visitors have an opportunity to see the Milky Way from nearly horizon to horizon, complete constellations, faint astronomical objects, and natural sources of light such as the Andromeda Galaxy, zodiacal light, and airglow.

The main impacts to Chaco's night sky quality were the light domes from Albuquerque, Farmington, Rio Rancho, Gallup, Crownpoint, Santa Fe, Bloomfield, and Grants. These light domes were observed along the horizon, with a few exceeding the natural brightness of the Milky Way. Additionally, glare sources associated with oil and gas development sites are visible along the north and east horizons. In a dark environment such as Chaco Culture NHP, small changes of lighting will have a large impact on the night sky quality. While effects from light domes and glare sources are moderate to low during clear nights, their brightness can be increased significantly by clouds and increases in atmospheric aerosols (e.g. dust, soot).

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The authors would like to acknowledge staff at Chaco Culture National Historical Park for their support in this fieldwork and logistics, notably Brad Shattuck, G.B. Cornucopia, Jennifer Frost, Jim Von Haden, Katherine Earp, and Nathan Hatfield. We acknowledge Chad Moore for his leadership and guidance in the implementation of night sky photometry in NPS units. We also thank the peer reviewers for recommendations that improved this series of reports.

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, data quality and anomalies, glare, and long-term trend 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 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 obscures celestial objects. This 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.

Chaco Culture National Historic Park is located near the geographic center of the San Juan Basin of northwestern New Mexico and the adjacent "Four Corners" states (Figure 1). The park is in a semi-arid desert steppe. The nearest populated center is Farmington, about 80 km north of the park. Albuquerque and Santa Fe, the most populous cities in the state, are 160 km and 190 km southeast of the park respectively. No large cities are within 80 km of the park, but development in small communities of Nageezi to the northeast and Crownpoint to the south can also increase skyglow that affects the park.

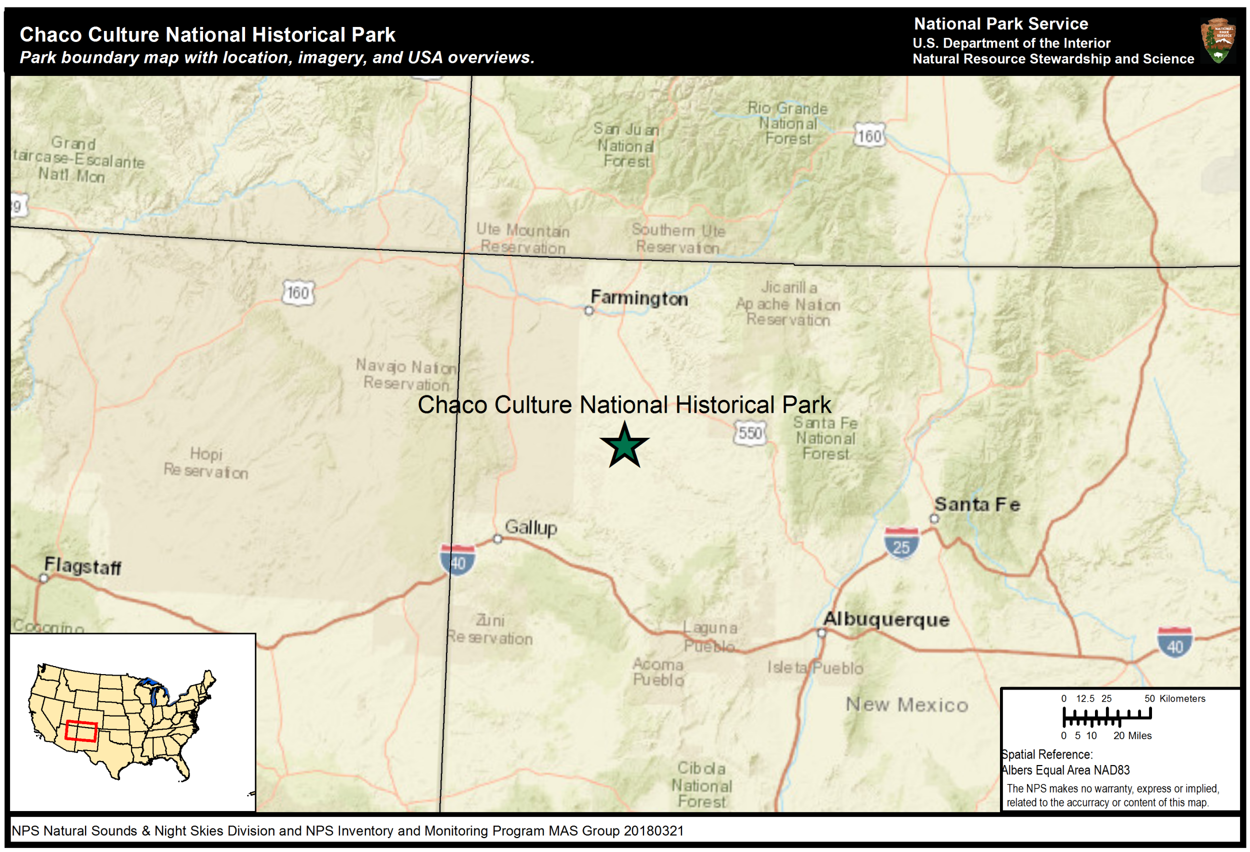


Figure 1: Geographic location of the park. Chaco Culture NHP is located near the center of the San Juan Basin of northwestern New Mexico and the adjacent "Four Corners" states. In general, light sources within 300 km could be visible and have the potential to brighten the night sky.

Methods

Imaging the Night Sky

The NPS developed the camera system and the observing method to collect high-resolution images of the night skies 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 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: 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.

Over the period from 2001 to 2016, NPS has collected nine nights of ground-based CCD camera data in Chaco Culture NHP, yielding twenty-three 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.

Table 1: Ground-based data collection events at Chaco Culture NHP

Date	Site Name	Camera	Sets	Observers
2001-10-13	Water Tank	Apogee	1	D Duriscoe, C Moore, C Duriscoe
2003-01-28	Water Tank	Apogee	1	C Moore, A Richman
2003-01-30	Water Tank	Apogee	1	C Moore, A Richman
2005-03-10	Water Tank	IMG1	4	K Peterson
2008-05-29	Water Tank	IMG2	2	K Magargal, D Duriscoe
2008-05-30	Water Tank	IMG2	4	K Magargal, D Duriscoe
2013-05-31	Gallo Cuesta	ML4	8	J White, B Meadows, J Von Haden
2014-05-08	Pueblo Alto	ML3	2	M Nelson, J Briggs
2016-09-23	Kin Kletso	ML3	3	L Hung, A Reed

Note: 'Sets' refers to the number of data sets taken that night; each set yields a panoramic image of the sky.

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 conditions representable 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, located on the map in Figure 3, and described in detail below.

Table 2: Data collection sites at CHCU

Site Name	Elevation (m)	Latitude	Longitude
Water Tank	1955	36.03153	-107.90854
Gallo Cuesta	2006	36.04025	-107.90461
Pueblo Alto	1965	36.07018	-107.95522
Kin Kletso	1905	36.06547	-107.96900

Water Tank

The Water Tank site is on the canyon rim above the visitor center parking lot. This site was selected for its accessibility by road and its relatively good view of the south and southwest horizons. The

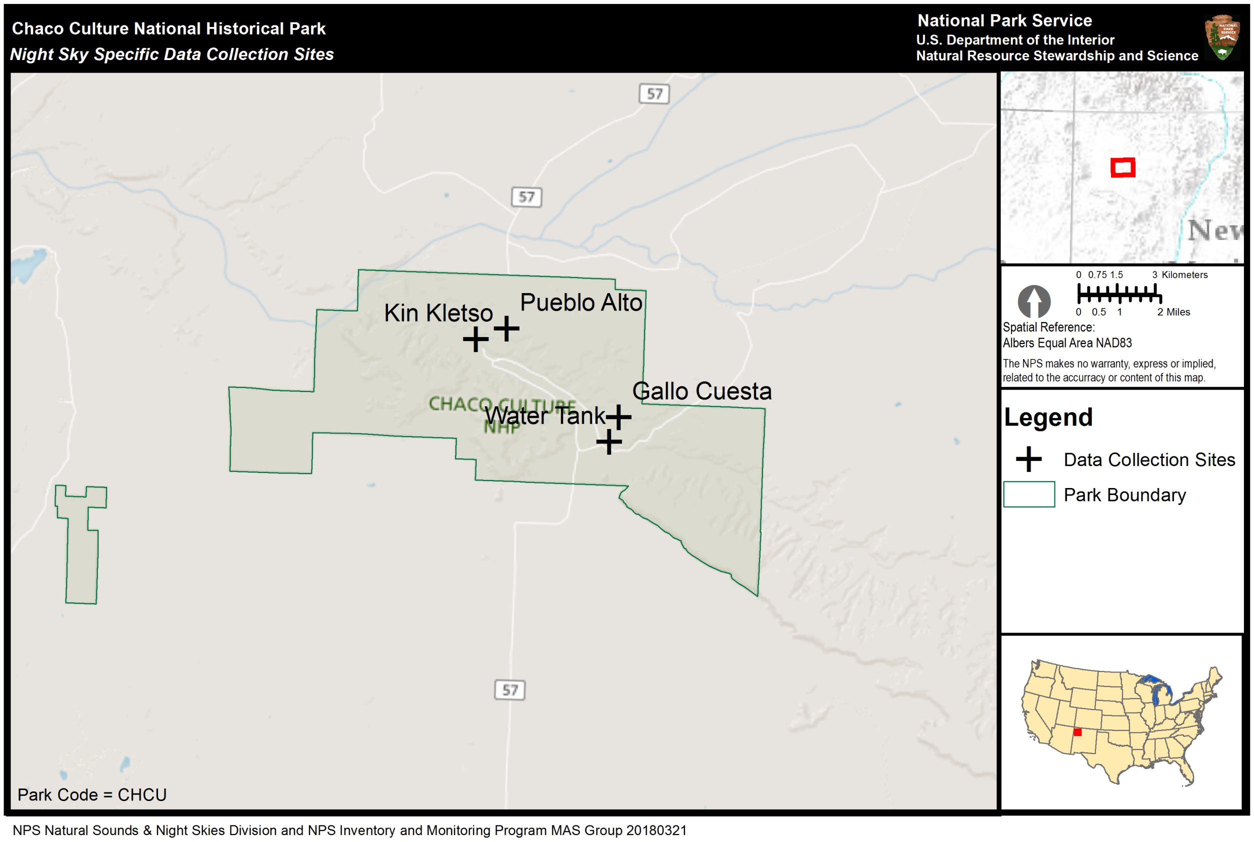


Figure 3: Map showing the data collection sites. The data were collected at four different places inside the park: the Water Tank on the rim above the visitor center parking lot, Gallo Cuesta northwest of sewage lagoons and north of the canyon rim, Pueblo Alto adjacent to the Pueblo Alto complex, and Kin Kletso on the north rim above the Kin Kletso complex.

northern horizon is blocked by the Gallo Cuesta plateau. This site also looks down onto the main facilities of the park.

Gallo Cuesta

The Gallo Cuesta observation site is northwest of sewage lagoons and north of the canyon rim. This site replaced the Water Tank site which was no longer accessible as of 2013 due to the newly installed water tank system. The Gallo Cuesta site was selected for its unobstructed 360° horizon view, and its line-of-site view of oil and gas development sites to the north and east of the park. The limited terrain blocking and high elevation provided an excellent vantage point in all directions. Data from this point served as a representation of the park outside of the main canyon.

Pueblo Alto

The Pueblo Alto observation site is adjacent to the Pueblo Alto complex. This site was chosen primarily to enable the sky quality measurement to be made with acoustic sampling in the same field trip to maximize the data collection efficiency. This site is next to an important cultural site and has an unobstructed 360° horizon view, including the existing oil and gas development.

Kin Kletso

The Kin Kletso observation site is located on the north rim of the canyon above the Kin Kletso complex. This location was selected in response to an access issue to the Gallo Cuesta site that night and for its relatively easy accessibility compared to the Pueblo Alto site.

Processing Night Sky Images

For each data set, we process the images to generate a panoramic view of the night sky with the 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 yield 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 International Dark-Sky Association proposed using the Walker's Law in the following form:

$$I \;=\; 0.01\;P\;d^{-2.5} \tag{1}$$

where I is the Walker's value indicating the skyglow level above the natural background, P is the human population size taken from 2010 US Census Data, and d is the distance to the population center. At each observing location, we calculate the azimuth and apparent width of each population center nearby based on the city centroid and the recorded city area.

The light dome brightness predicted by Walker's Law might not perfectly match what is captured in the images. There is a known trend that a closer city tends to contribute more skyglow than the value calculated using Equation 1. 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 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. The DNB has a swath width of 3000 km and the pixel resolution of 742 m. The satellite has an orbital period of $\sim$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 NOAA website[1]. The VIIRS DNB sensor has on-orbit radiometric calibration and reports the radiance in units of $W \cdot cm^{-2} \cdot sr^{-1}$ (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 2016 for the following analysis.

We use the satellite imagery to estimate sky quality through a simple predictive model (Duriscoe et al., 2018). The 2016 annual composite from VIIRS DNB serves as a map of upward nighttime lights for our model input. The simplified model of all-sky artificial skyglow (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.

[1] https://www.ngdc.noaa.gov/eog/viirs/download_dnb_composites.html

Results

The ground-based observations yield the calibrated panoramic images of the night sky. Figure 4 shows an example of the image product associated with each data set. In Appendix A: Observation Notes and Panoramic Images, we provide a complete gallery of the reference image for each night. We use magnitude per square arcsecond (mag/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. A sky surface brightness of 22 mag/arcsec^2 would be considered pristine, and a sky surface brightness < 20 mag/arcsec^2 would be considered greatly deviated from the natural condition. The warmer colors in these images represent brighter skies. Figure 4(a) shows the observed night sky, which contains light from both natural and artificial sources. Purple and dark blue colors indicate unpolluted sky, and the Milky Way under the natural condition appears green in this color scheme. Figure 4(b) shows only the light from artificial sources. Light domes along the horizon from the nearby area are more apparent in this bottom image.

In the images, the largest and brightest cluster of light domes is from the city of Farmington and Bloomfield in the north. The light dome from Albuquerque and its suburb Rio Rancho closely follows in the southeast. Neither cluster appears to extend more than thirty degrees above the horizon, however, and the brightest parts are comparable to the brightest part of the Milky Way. The cities of Gallup and Crownpoint have small but bright light domes along the southwest horizon. Note that the core brightness of a light dome and its overall size are not correlated in all cases. Albuquerque provides an example of a large, distant city with the second largest light dome (width and height) but with a more modest core brightness than some other smaller light domes such as Gallup. Overall, the majority of the sky is free of artificial skyglow.

In Table 3, we listed the nearby cities from the Water Tank 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.

Table 3: Nearby cities and their predicted skyglow impact at the Water Tank site

Place	Population in 2010	Distance (km)	Azimuth (degree)	Width (degree)	Walker's Value (% above natural)
Albuquerque	545,852	154	132	9.2	1.87
Farmington	45,877	84	344	7.0	0.71
Rio Rancho	87,521	137	127	7.8	0.40
Gallup	21,678	95	233	4.8	0.25
Crownpoint	2,278	44	210	6.2	0.18
Santa Fe	67,947	179	103	4.0	0.16
Bloomfield	8,112	78	355	3.8	0.15
Grants	9,182	98	176	4.0	0.10

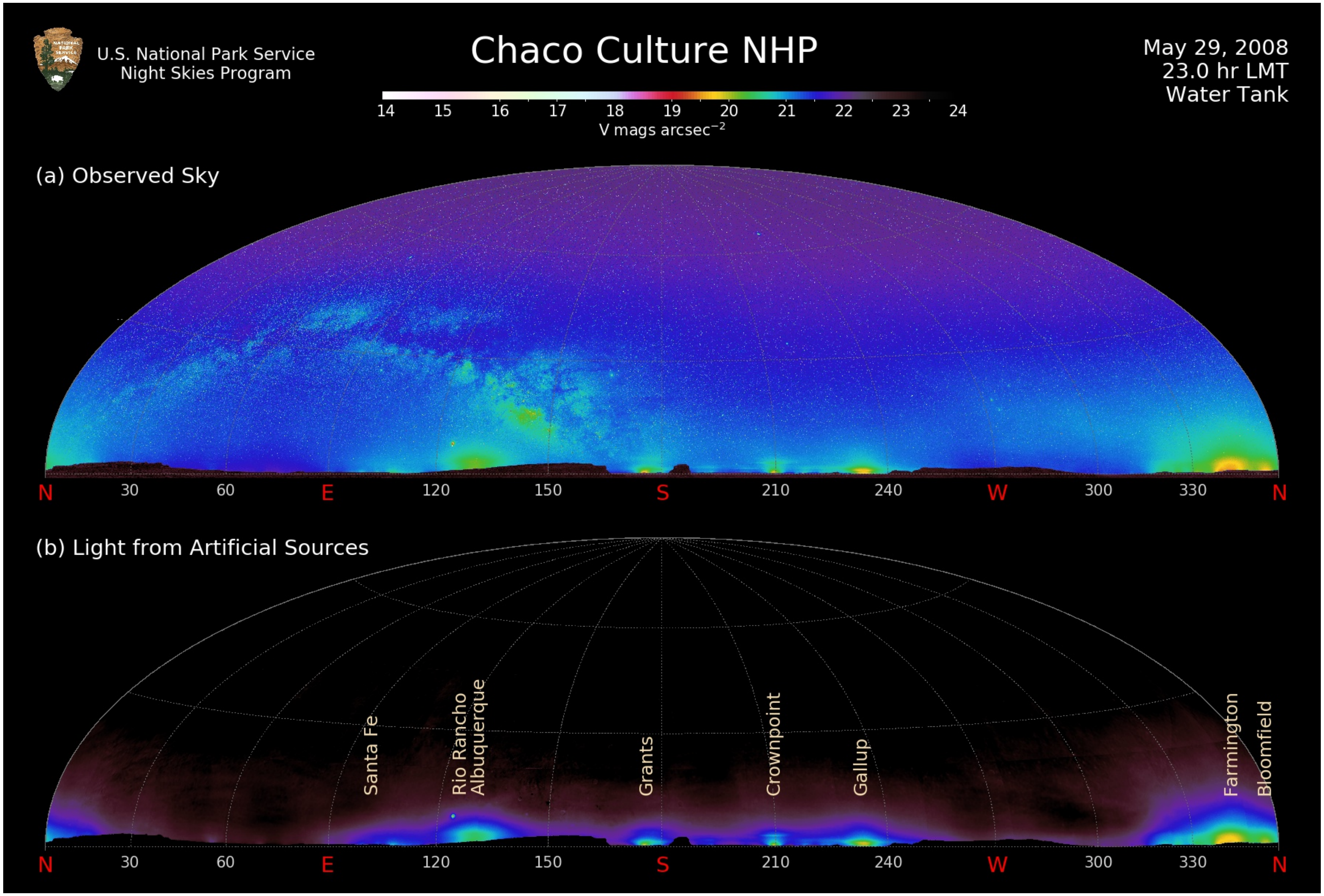


Figure 4: Panoramic image of the night sky from the Water Tank site on May 29, 2008. The grid lines are spaced 30° apart. (a) The observed sky showing light from all sources, both natural and artificial. (b) The image of estimated skyglow from artificial sources. The natural light has been removed from this image, showing only the artificial skyglow and associated light domes.

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 lost stars, and all-sky light pollution ratio (ALR). If multiple data sets were taken in a night, we report 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 visual assessment on Bortle Class and naked eye limiting magnitude (NELM) and take readings with a Unihedron Sky Quality Meter (SQM) whenever possible. A description for each of these metrics is provided below.

Table 4: Chaco Culture NHP sky brightness metrics derived from the observed images

Date	Time (hh:mm)	Horizontal Illuminance (mlx)	Max. Vertical Illuminance[a] (mlx)	Zenith Brightness (mag/arcsec^2)	Lost Stars (%)	All-sky Light Pollution Ratio
2001-10-13	23:27	1.03	0.67 [260°]	21.72	2	0.15
2003-01-28	00:35	0.70	0.47 [280°]	21.96	2	0.13
2003-01-30	23:17	0.81	0.54 [310°]	21.86	1	0.12
2005-03-10	21:47	0.91	0.63 [300°]	21.76	1	0.15
2008-05-29	22:59	0.73	0.52 [145°]	22.21	2	0.16
2008-05-30	23:17	0.70	0.51 [150°]	22.23	2	0.12
2013-05-31	22:14	0.95	0.70 [330°]	21.87	2	0.19
2014-05-08	02:24	0.98	0.71 [015°]	21.84	6	0.42
2016-09-23	22:28	0.73	0.45 [240°]	21.91	11	0.13
Urban Sky[b]	—	39.56	29.04	18.00	92	64.43
Natural Sky[c]	—	0.80	0.40	22.00	0	0.00

[a] Values shown in the square brackets are the associated azimuthal angles.
[b] Rock Creek Park in Washington, DC was used as the urban sky reference.
[c] 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 nine observation nights in Chaco Culture NHP, the average horizontal illu-

Table 5: Chaco Culture NHP visual and SQM measurements

Date	Bortle Class	Limiting Magnitude	SQM (mag/arcsec^2)
2001-10-13	3	6.8	—
2008-05-29	3	7.0	—
2008-05-30	3	7.0	—
2013-05-31	3	7.1	21.54
2014-05-08	—	7.1	21.74
2016-09-23	3	—	—
Urban Sky[a]	8	5.2	18.36
Natural Sky[b]	1	7.0	22.00

[a] Rock Creek Park was used as the urban sky reference.

[b] The median natural sky is the natural reference condition.

minance is only slightly higher than the natural reference. The measured horizontal illuminance values indicate the park preserves to a large extent of the natural illumination on the plain.

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 and its associated azimuthal angle. Note that the maximum vertical illuminance can be greatly influenced by natural sources such as the Milky Way, zodiacal light, and airglow. From the nine observation nights in Chaco Culture NHP, the maximum vertical illuminance from all sources is less than one mlx (about one tenth of a quarter moon) but greater than the referenced natural value of 0.40 mlx in all observations. This result shows how artificial lights have a measurable effect in brightening the night sky along the horizon. Nonetheless, the overall illuminance level is still low for providing a refuge for crepuscular and nocturnal species in the park.

The zenith sky brightness is the sky brightness 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/arcsec^2, and the brightest part of the Milky Way is about 20 mag/arcsec^2. Overall, the photometric measurements in Chaco Culture NHP show the zenith is very dark, and skyglow at zenith is not measurable. The sky overhead remains pristine with the average zenith brightness of 21.9 mag/arcsec^2.

The lost star metric concerns the percentage of stars that become invisible under 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 nine observation nights in Chaco Culture NHP, we estimate more than 90% of stars were still visible for most of the time, 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 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 indicate excellent conditions, 0.3 to 2.0 indicate impaired sky quality (though areas of the sky may reveal important natural features), and greater than 2.0 indicate the natural night sky is not readily visible. Excluding the observation taken in 2014 under hazy conditions, the whole sky over Chaco Culture NHP is only 12-19% brighter than average natural levels, indicating excellent dark sky conditions. In summary, values form the above indicators demonstrate only a very small amount of impact from light pollution has been measured in these sky luminance data.

Bortle Class is a nine-level numeric scale that measures the night sky's brightness of 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 Chaco Culture NHP, we classified the sky as Bortle Class 3 (rural sky) which generally indicates some light pollution exits along the horizon, the summer Milky Way still appears complex, and the zodiacal light is evident in spring and autumn.

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. 6.6 is considered near pristine under average conditions. 7.0 is achievable under good seeing conditions and with proper dark adaptation of the eye. 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.[2] In Chaco Culture NHP, the average limiting magnitude is 7.0, approaching the sensitivity limit of human eyes under good atmospheric conditions.

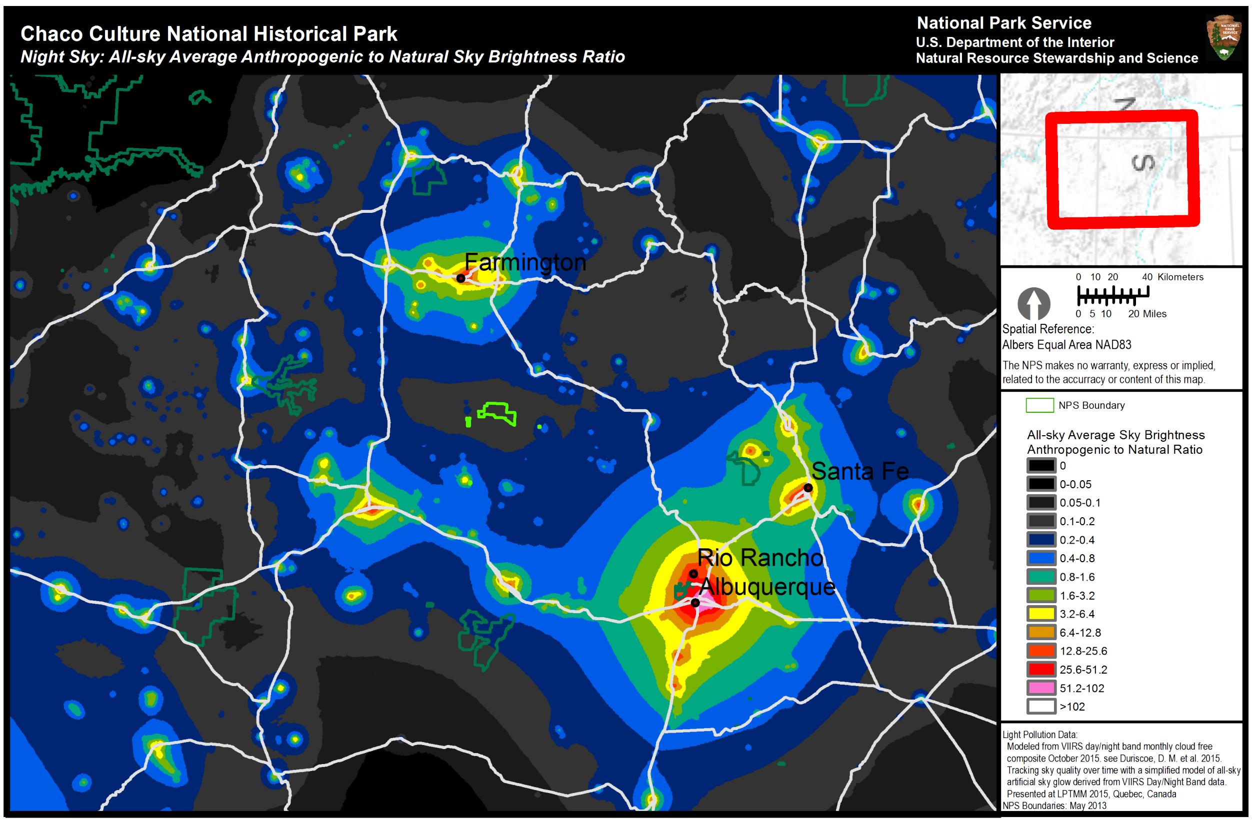
The hand-held Sky Quality Meter (SQM) is an economic and convenient tool to take a single value of sky brightness measurement with just one click. We point SQM towards zenith when taking a reading. The SQM has a wide field of view; its full width half maximum of the angular sensitivity is $\sim 42^{\circ}$. 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/arcsec^2. Our SQM measurements in

[2] https://www.globeatnight.org/maps.php

Chaco Culture NHP average to 21.6 mag/arcsec^2, indicating the zenith is darker than what we can accurately measure with a SQM.

Regional Sky Brightness Model

Figure 5 displays regional predictions of skyglow based on the SALR model using the annual 2016 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 in the center with the surrounding area to approximately 300 km. This map provides a landscape view of the average sky brightness in and around the park. The scale on the right 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.



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Park Code = CHCU

Figure 5: A model of average all-sky light pollution ratio (ALR) in the region surrounding Chaco Culture National Historical Park. The park is placed in the center of the map with the park boundary outlined in light green. The white lines represent the major roads.

Chaco Culture NHP is nearly surrounded by light sources, but at distances great enough to produce minimal predicted impact. In the large communities such as Albuquerque, Rio Rancho, Farmington, and Santa Fe, the sky quality is dramatically different than in the park. In Figure 5, red corresponds to the condition at which extended features of the night sky (e.g. Milky Way and

Andromeda Galaxy) are invisible in early all situations, constellations become difficult to identify, and the sky is colorized by the numerous lights. Chaco Culture NHP is mostly in gray color (values ranging from 0.1 to 0.2), which agrees with all the measurements taken inside the park except for the 2014 observation taken under hazy conditions. 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 mask 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 lost star 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, 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 close-by sources but diminish the brightness of distant sources. Figure 6 illustrates the appearance of the same light dome under different atmosphere conditions. While these observations were taken in different years and are not from the exact same site, the significant increase in skyglow in 2014 is most likely attributed to the higher aerosol content at the time of the observation in comparison to other years. Variation in aerosol content can affect the sky brightness measurements even with no net increase of 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.

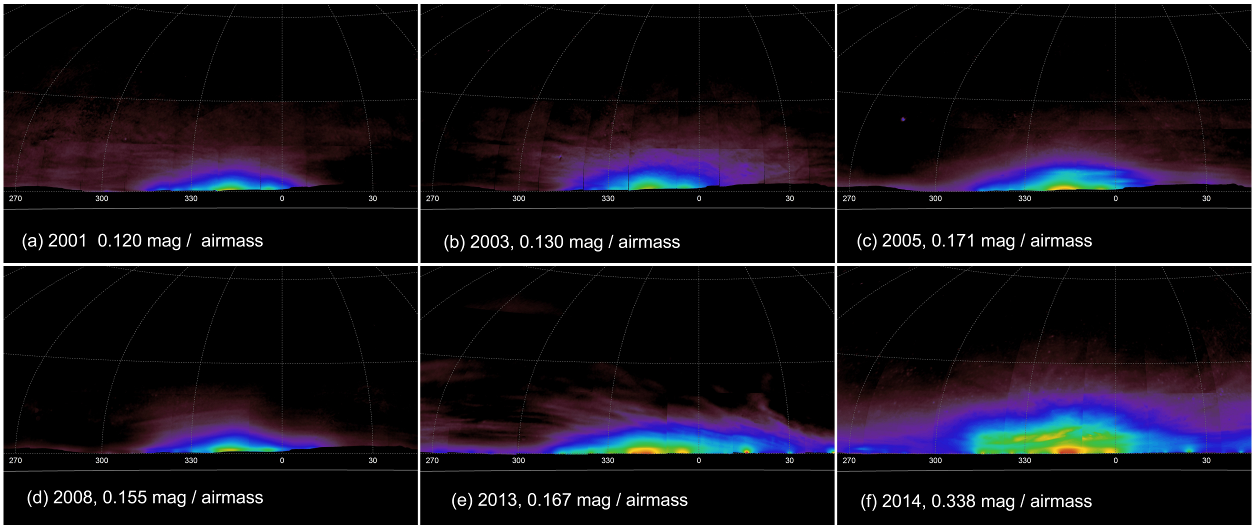

Figure 6: Close up on Farmington/Bloomfield light dome in New Mexico as seen from Chaco Culture NHP. The year and measured extinction coefficient are listed for each panel. Increasing the aerosol content in the atmosphere will increase the extinction value. While these observations were taken at different times and are not from the exact same site, the significant increase in skyglow in 2014 is most likely attributed to the higher aerosol content.

Data Quality and Anomalies

The data sets collected in 2014 are not ideal for assessing the night sky quality due to the hazy observing condition and the presence of thin clouds. Extinction values indicate the quality of atmosphere transparency. Increasing the aerosol content in the atmosphere will increase the extinction value. The measured atmospheric extinction that night was 0.34 mag/airmass, which indicates poor atmospheric conditions. For the elevation of this site, extinction with no aerosols in the atmosphere is predicted at 0.11 mag/airmass. Aerosols from the haze, dust, and air pollutants are enhancing the skyglow. In addition, clouds over the cities Farmington and Gallup reflected the light domes. The thin clouds and high atmospheric extinction render the 2014 data not ideal for photometry.

Glare

Glare is bright and uncomfortable light shining from the source directly to the observer. In general, common glare sources include outdoor lights from the 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. Our images show that along the north and northeast horizon at Gallo Cuesta, several drilling operation lights and gas flares created direct glare. Local glare sources affecting Chaco Culture NHP include exterior lights on administrative and public facilities, gas flaring, and temporary unshielded lighting such as drilling rigs.

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 the actual lighting level change. Before this variation is well understood, we cannot use the satellite data to identify the trend.

North of the park, a few new developments were observed visually and in the images (Figure 6) over the course of data collection. An increase in energy development north of the park is known to have taken place since 2010. Comparing the images taken in 2013 and 2014 to the ones from prior years, more isolated and distinct light domes appeared in the observations. In the 2016 data, the northern horizon was blocked by the terrain so the light domes were not captured in the images for comparison.

Conclusions

Overall, the night sky conditions at Chaco Culture National Historical Park are very good. The measured sky brightness averaged over the whole sky is only slightly brighter than the natural conditions, allowing 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, visitor 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.

The greatest impacts to night sky quality are the light domes of Albuquerque, Farmington, Rio Rancho, Gallup, Crownpoint, Santa Fe, Bloomfield, and Grants. These light domes were observed along the horizon, with Albuquerque, Farmington, Rio Rancho, Gallup, and Crownpoint light domes exceeding the natural brightness of the Milky Way. Additionally, glare sources not associated with cities are visible along the north and east horizons; these glare sources were found to originate from oil and gas development sites. Other glare sources affecting the park include exterior lights on administrative and public facilities locally. In a dark environment such as Chaco Culture National Historical Park, small changes in artificial light distribution, color, or brightness will be noticeable. While impacts from light domes and distant glare sources 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.

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: light only if needed, light only when needed, light only where it is needed, use warm-white or amber light, use the minimum amount of light needed, and use energy-efficient lights. Locally, appropriate lighting in the park can provide visitors the optimal observing environment. Partnering with gateway communities can further reduce light pollution, both locally and regionally. Reducing light pollution improves the quality of night sky viewing and increases park visitation. 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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Glossary

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 at the 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 degree 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 twilight.

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 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 brightness 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 varies with the seasons and the nightly motion of the sky.

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 the 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: Light traveling upwards.

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 reflected off the dust particles in orbit around the sun.

Appendix A: Observation Notes and Panoramic Images

On October 13 2001, visual observations indicated excellent atmospheric transparency but with moderate turbulence. Overall the sky was observed to be very bright from natural airglow, with small light domes visible along the horizon from this high vantage point. No direct glare from light sources at any distance was observed. A very good fit to a model of the natural sky was achieved despite the high natural airglow. Subtraction of the natural background reveals the skyglow sources near the horizon in high contrast to the essentially unaffected zenith area. The data is free of clouds and plumes of dust or smoke in all directions.

On January 28 2003, the presence of some high clouds reflected some of the artificial light. On the 30th, the sky was clear, and the data quality was better. Both nights appeared to have very low amount of natural airglow and excellent air transparency, as is typical of the winter months at this site.

On March 10 2005, zodiacal light is apparent in the first data set above the western horizon, azimuth 290 degrees. Airglow is moderate to low with slight banding to the north. The Milky Way was visible as a near complete band from the southern horizon arching to near 60 degrees overhead into the northern horizon, and disappearing into the light dome of Farmington, NM, azimuth 340 degrees. Atmospheric conditions were stable and relatively clear over the course of the night. The night had good atmospheric conditions, but not among the best for this elevation.

On May 29-30 2008, airglow activities were low. The first night was hazy, by the following night the transparency improved. Milky Way details were striking. Light domes from several distant cities were observed; nearly all of these were small and faint except the Albuquerque and Farmington areas, which produce a significant impact to an otherwise essentially pristine night sky. No direct glare from light sources at any distance was observed. Interestingly, Farmington appears brighter on the 29th than on the 30th while the brightness of the Albuquerque light dome exhibits the opposite. This would be expected, since Albuquerque is much further away from the observing site than Farmington and the increased haze results in attenuation of light originating at a distance and amplification of skyglow from relatively close sources.

On May 31 2013, the sky was in relatively clear conditions but not among the best for this elevation. Bright glare sources along the horizon are visible. Artifacts of banded airglow are seen between ten and 30 degrees above the horizon. At zenith, the skyglow is not measurable.

On May 8 2014, the atmospheric conditions were poor, especially for this elevation. In the full-resolution mosaic, bright glare sources along the horizon are visible. At the zenith, the artificial sky brightness is not measurable. Clouds over the cities Farmington and Gallup are reflecting the light domes. Aerosols from the haze, dust, and air pollutants are enhancing the skyglow.

On September 9 2016, the sky was clear. Direct glare is not visible from this site. Airglow bands are apparent in the images near the horizon. The data quality is good.

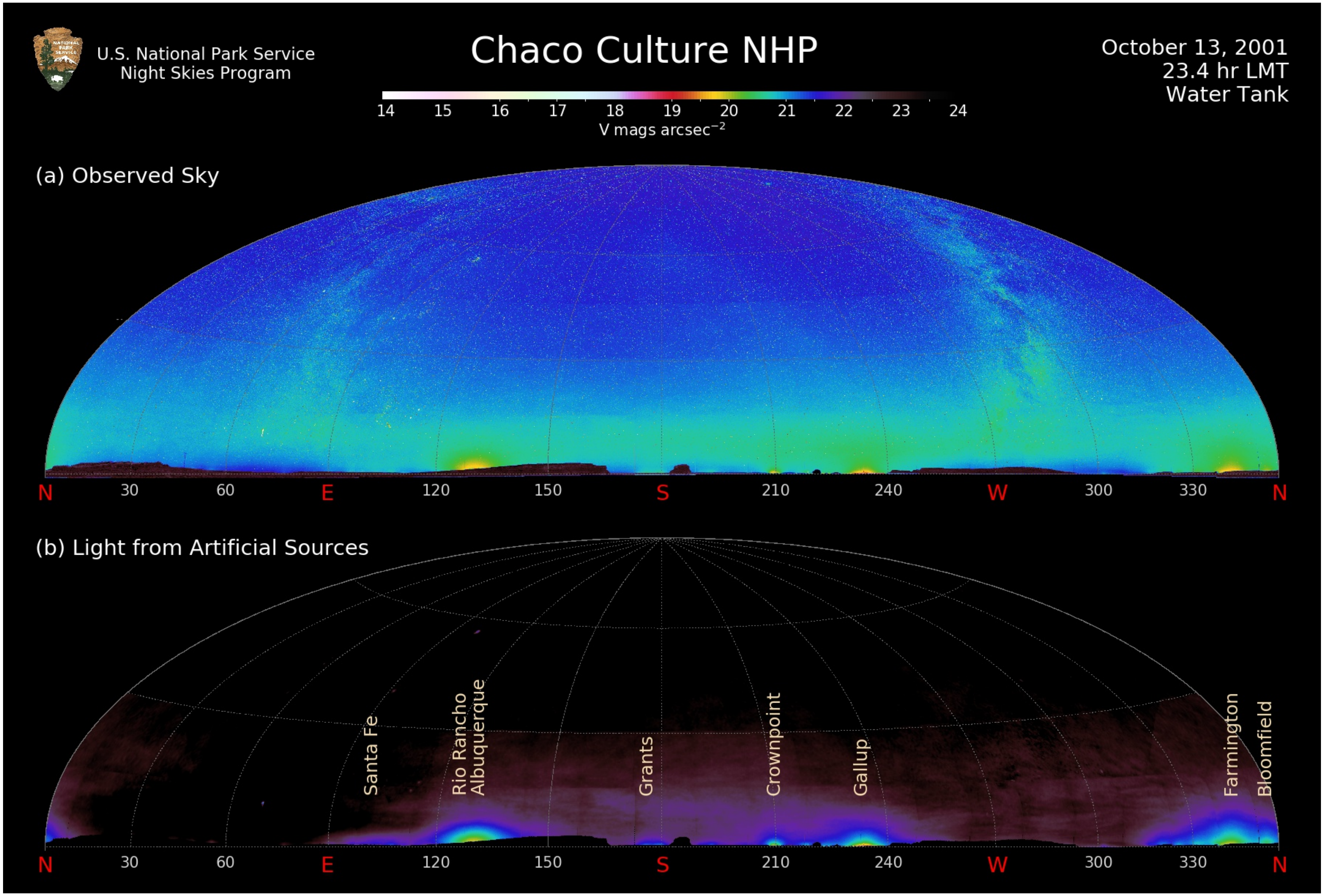

Figure 7: Panoramic night sky images from the Water Tank site on 10/13/2001. (a) Observed night sky. (b) Light from artificial sources.

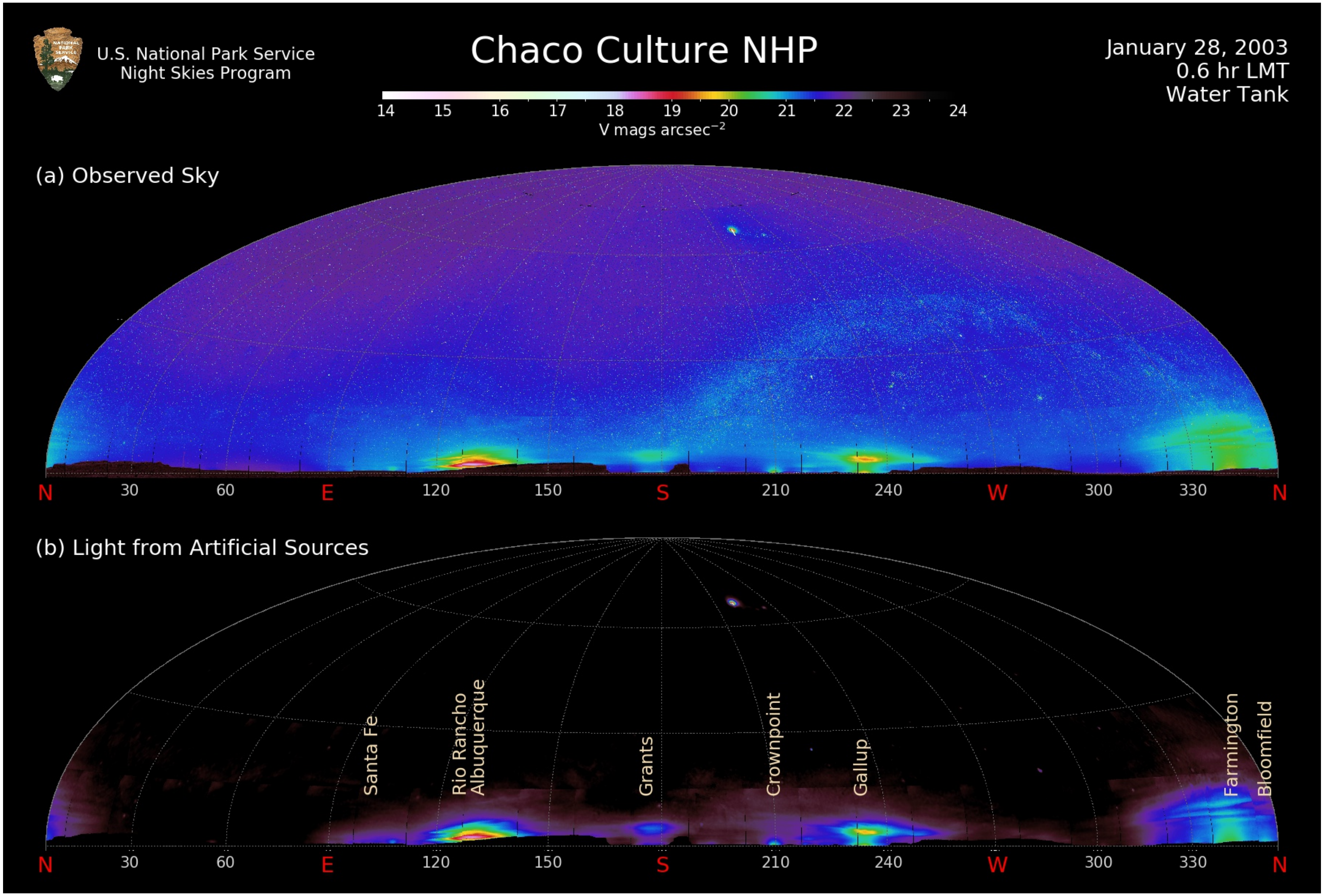

Figure 8: Panoramic night sky images from the Water Tank site on 01/28/2003. (a) Observed night sky. (b) Light from artificial sources.

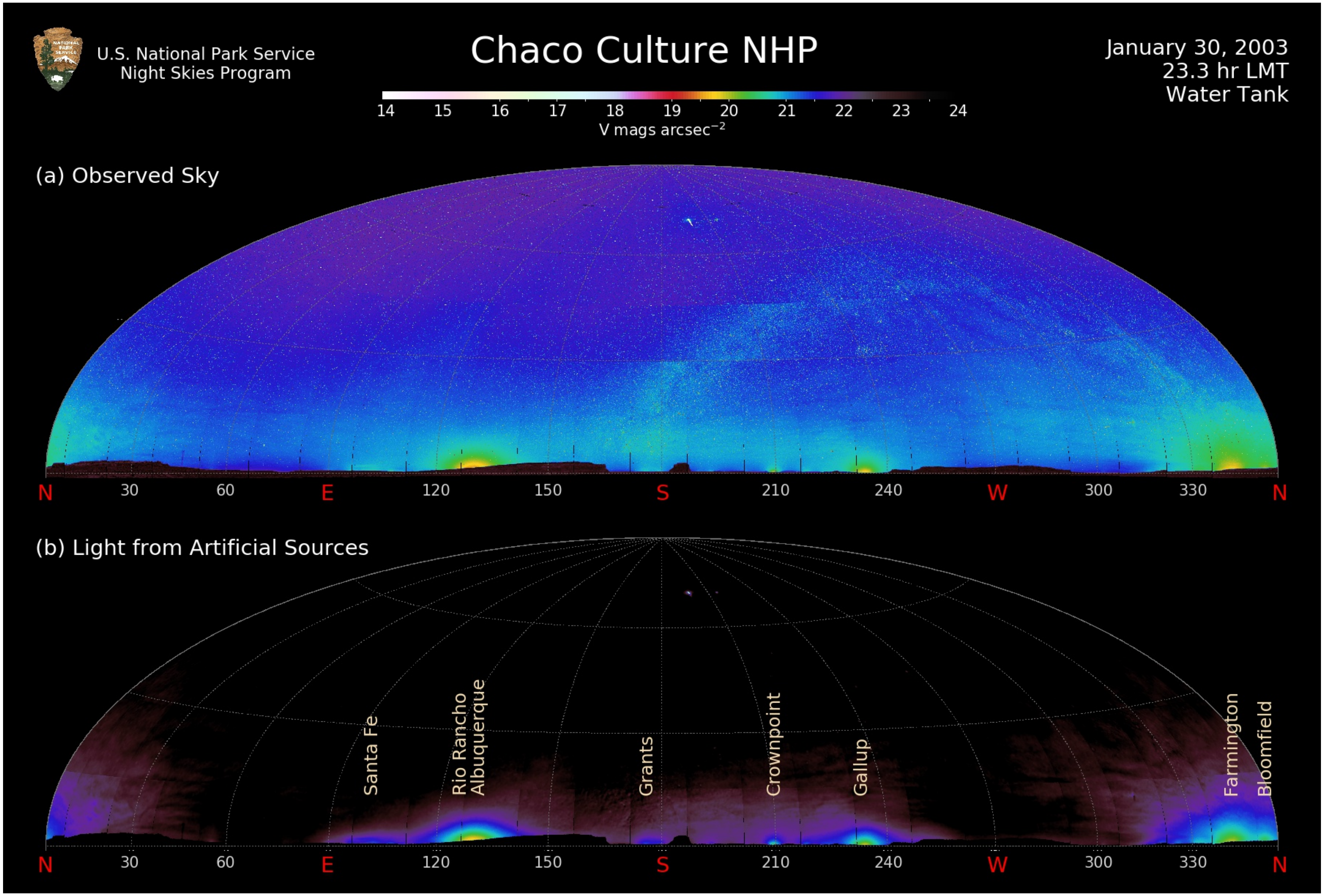

Figure 9: Panoramic night sky images from the Water Tank site on 01/30/2003. (a) Observed night sky. (b) Light from artificial sources.

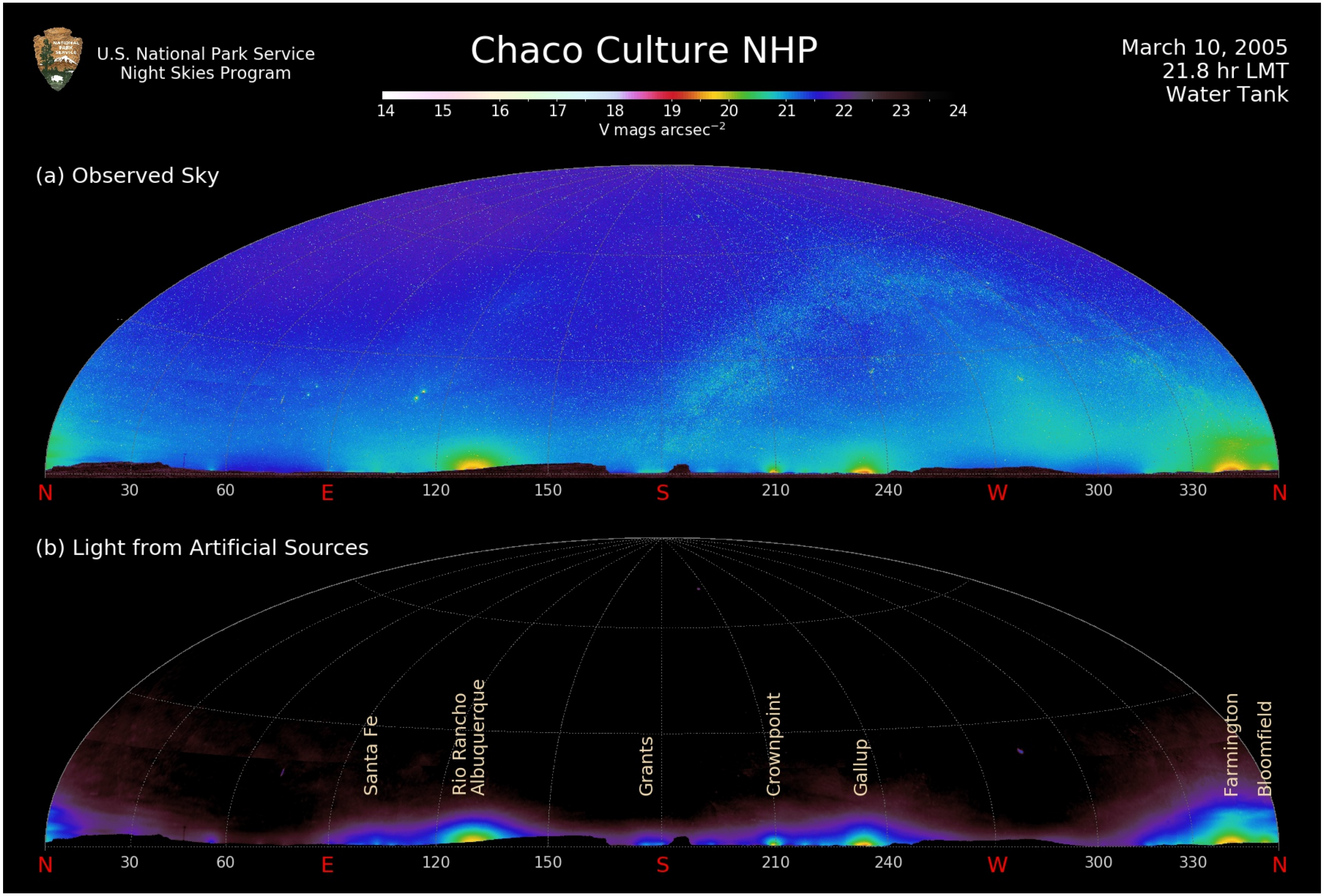

Figure 10: Panoramic night sky images from the Water Tank site on 03/10/2005. (a) Observed night sky. (b) Light from artificial sources.

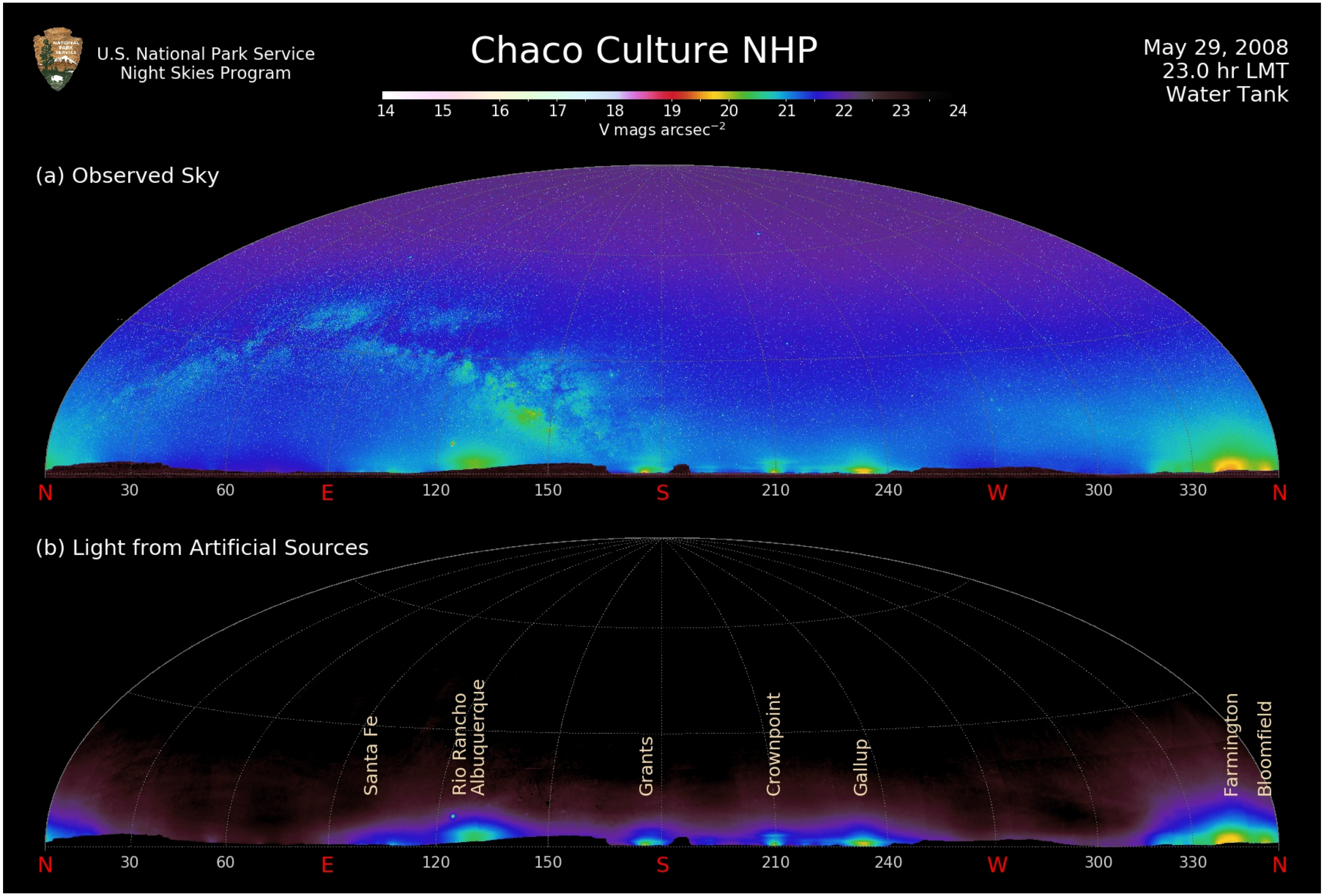

Figure 11: Panoramic night sky images from the Water Tank site on 05/29/2008. (a) Observed night sky. (b) Light from artificial sources.

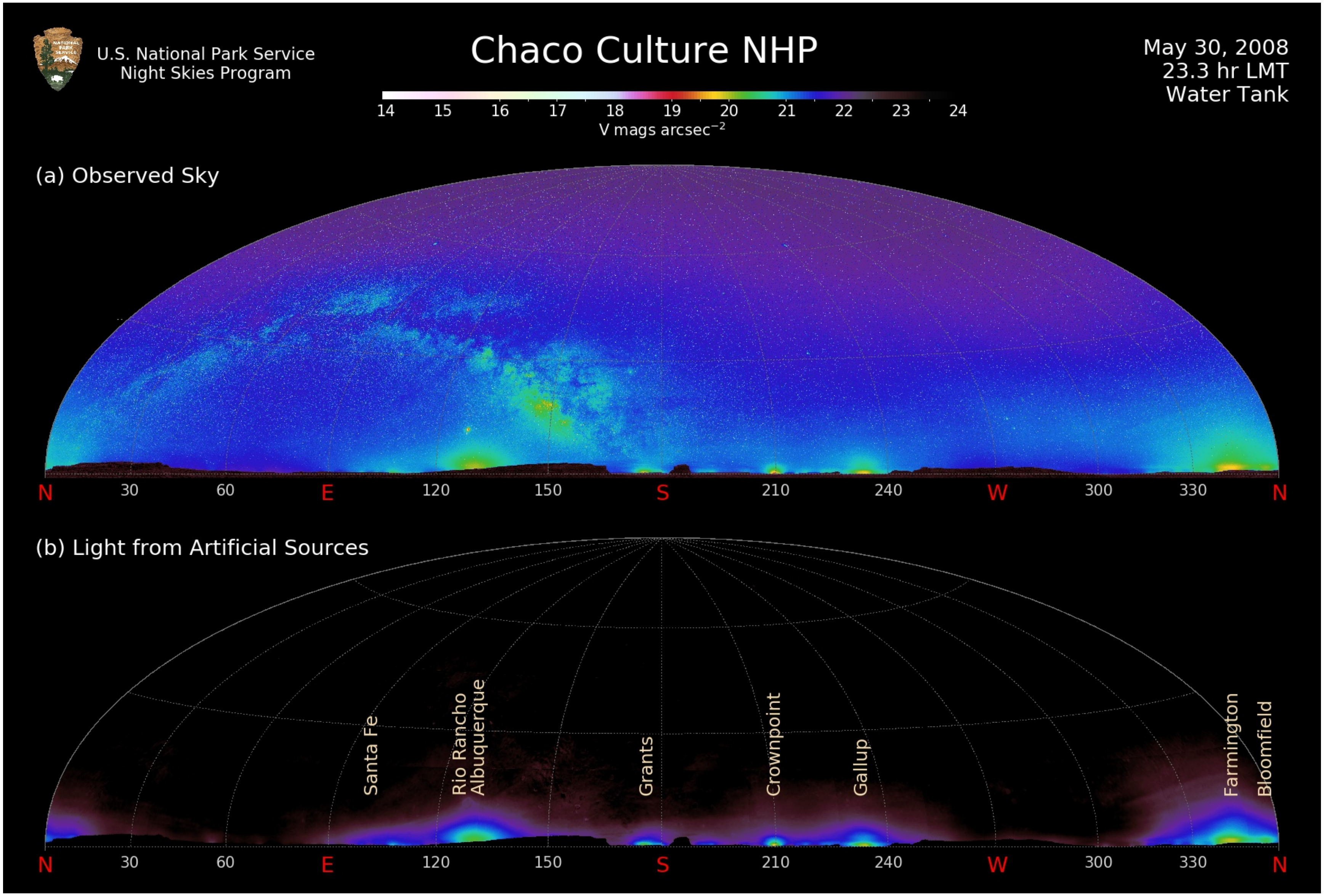

Figure 12: Panoramic night sky images from the Water Tank site on 05/30/2008. (a) Observed night sky. (b) Light from artificial sources.

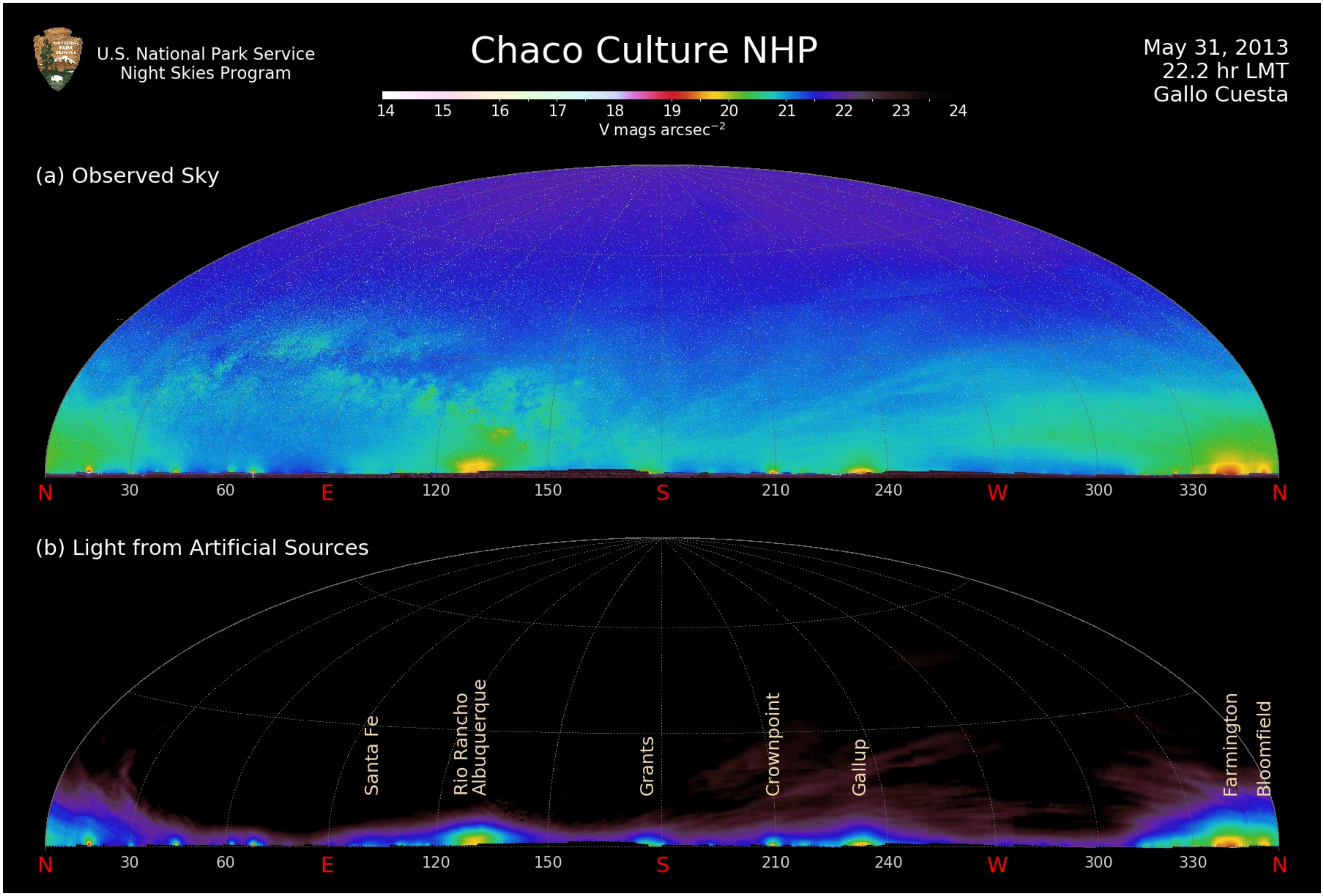

Figure 13: Panoramic night sky images from the Gallo Cuesta site on 05/31/2013. (a) Observed night sky (b) Light from artificial sources

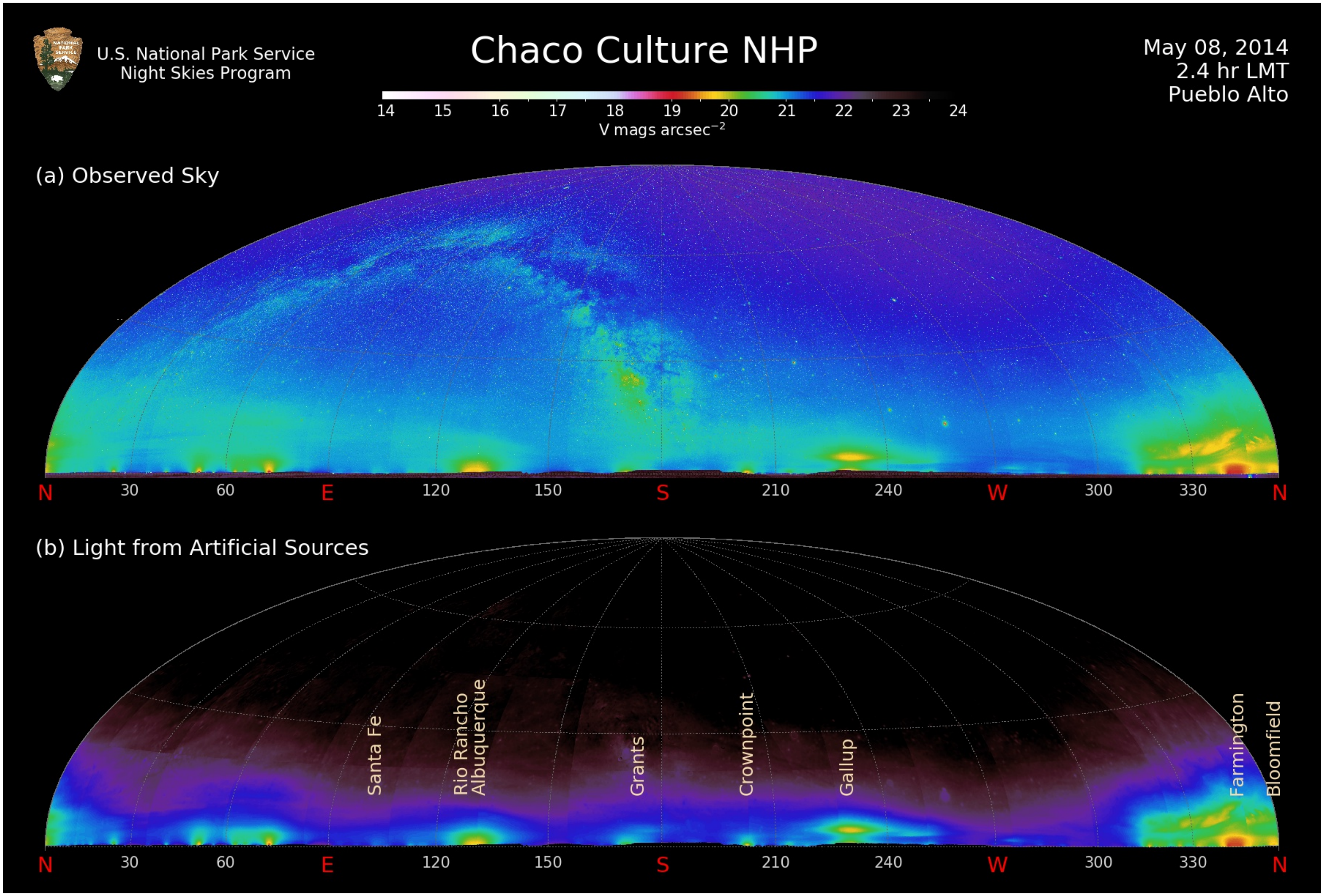

Figure 14: Panoramic night sky images from the Pueblo Alto site on 05/08/2014. (a) Observed night sky. (b) Light from artificial sources.

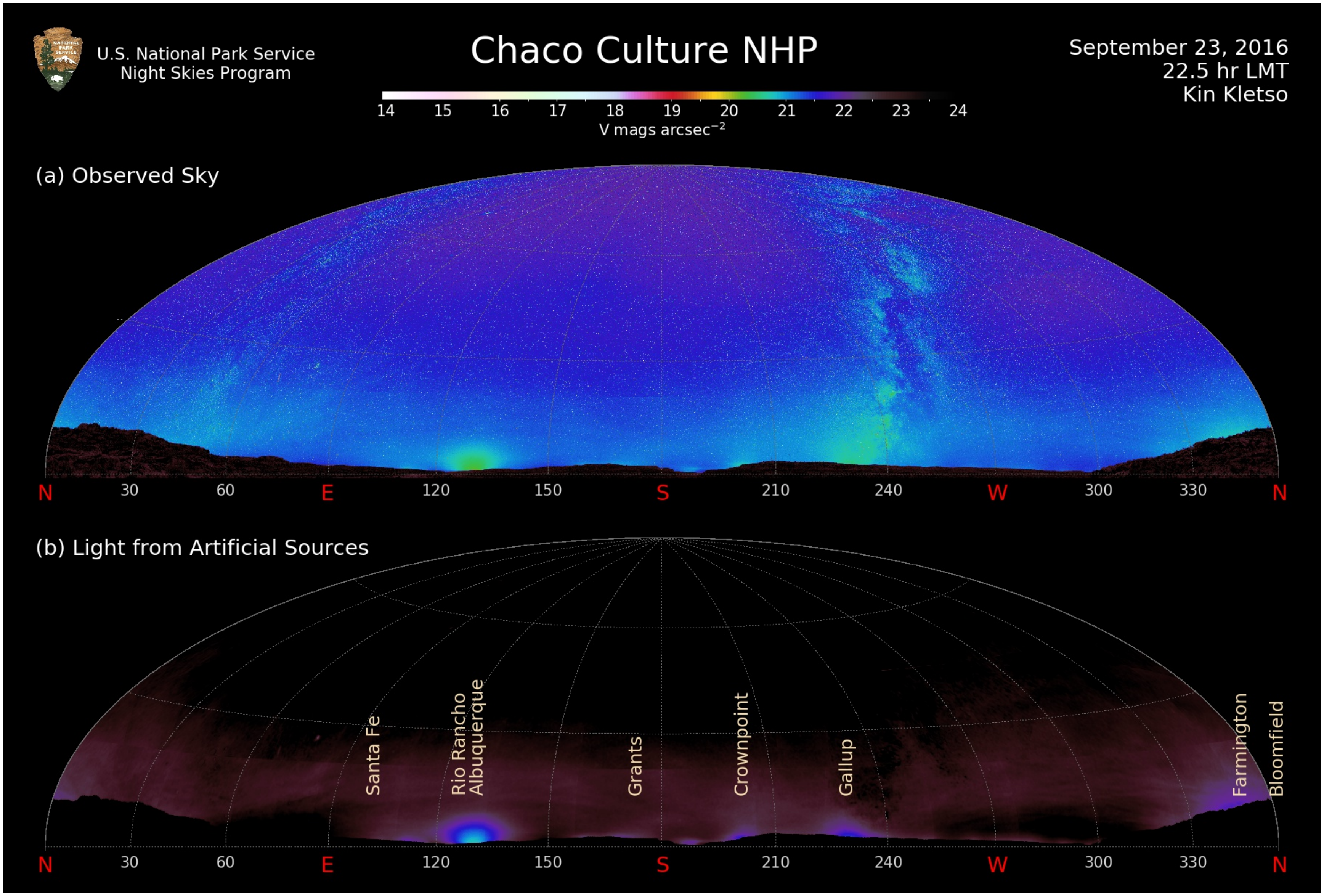

Figure 15: Panoramic night sky images from the Kin Kletso site on 09/23/2016. (a) Observed night sky. (b) Light from artificial sources.

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