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FINAL REPORT:
DARK-SKY MEASUREMENTS AT ORGAN PIPE NATIONAL MONUMENT

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Abstract

The goal of this project is to find a simple method for measuring night-sky brightness to an accuracy of 10% or better. Sky brightness measurements are needed for any long-term assessment program of the effects of light pollution on night-sky quality. The National Parks and Conservation Association (NPCA) stated that "The National Park Service must be proactive and lead by example to aggressively reduce sources of light pollution within the national parks." We have modified the Night-sky Brightness Monitoring Protocol previously developed at Organ Pipe Cactus National Monument (ORPI) in order to make it quicker and easier to execute. This technique uses a small telescope to do aperture photometry and is now simplified to where one person can accomplish the data collection in three hours. In an effort to further streamline data collection we have explored using wide-field CCD imaging in parallel with the modification of the current protocol. Full-sky data collection has been conducted four times at ORPI, at Kitt Peak National Observatory, at Saguaro National Park East and West, and at Vega-Bray Observatory. Additional data collection has been done at Chiricahua National Monument (CHIR), Jarnac Observatory, and Tumamoc Hill Observatory. Along with the measurement experiments, important information has been gleaned about the relationship between atmospheric conditions and night-sky brightness. It has become clear that otherwise photometric (cloud-free) skies vary greatly (up to one magnitude per square arcsecond) in night-sky brightness, depending on the amount of particulates and moisture in the atmosphere above the observing site.

Introduction

Interest in measuring night-sky brightness at national parks arose out of the concern that light pollution will detract from the wilderness value of the site. Organ Pipe Cactus National Monument was an early leader in recognizing the need to quantify and monitor the quality of night skies. ORPI personnel Dan Duriscoe and Jon Arnold sought a way to measure night-sky brightness to monitor degradation of the skies due to encroaching light pollution. Their hope was to quantifiably document the sky brightening so steps could be made to control nearby light pollution sources. Early efforts at ORPI involved imaging light pollution domes using conventional photography; however, variations in film developing made it difficult to get accurate brightness data. In 1994, one of us (DC) was charged with the task of developing a sky brightness monitoring protocol for ORPI that would give accurate quantifiable results. Use of CCD imaging was the first method investigated. It was found to have simple data collection, but complex calibration and data reduction problems. Photoelectric photometry was then investigated. It provided straightforward calibration and data reduction but required expertise in astronomy to perform data collection. The first data collection was conducted in March 1995 and resulted in the isophote map of the night-sky (Resource Management 1995). However, during the course of the next few years, key personnel with the requisite astronomical knowledge left ORPI. The remaining staff members lacked the expertise in astronomy to easily conduct the protocol. They also found it difficult to find an entire night when conditions were right and they were available to conduct data collection. It was also a great burden to perform an all-night data collection for very diurnal staff members. Data collection was attempted in 1996, but discontinued after that time.

The International Dark-sky Association (IDA) in association with the author, submitted a proposal to the Southwest Parks and Monuments Association (SPMA) to reinstitute ORPI data collection as well as to investigate simplifying the existing protocol and explore alternative methods for data collection.

Aperture Photometry

The original ORPI observing protocol involved taking observations at 220 points in the sky, sampling the entire sky at regular intervals in azimuth and elevation. The goal was to get complete and even coverage of the night sky in order to capture any light domes as well as thoroughly cover the high altitudes to determine the sky brightness near zenith. However, this data over sampled high altitude points protocol was excessively difficult for ORPI personnel and a reduced protocol is needed in order to get useful data in a reasonable amount of time.

Seasonal measurements were then attempted using the protocol given in Table 1 at ORPI. Due to battery problems, the autumn (November 28, 2000) measurement was unsuccessful. Data were collected on the nights of April 30 and September 22, 2000, and January 20, 2001. Isophote maps were produced for these dates (Figures 1, 2, 3).

Table 1. Data Collection Points for the Simplified ORPI Observing Protocol

Altitude	Azimuth Interval	Number of Points
5	10	36
10	20	18
20	30	12
30	45	8
45	60	6
60	90	4
90		2
	Total Points	86

In general, observing conditions throughout much of the year 2000 were poor. The April sampling occurred after one of the driest winters on record. Winds during the day before sampling loaded the atmosphere with particulates. The sky appeared gray which led to an increase in overall sky brightness and an enhancement of the Sonoyta light dome. The Phoenix sky glow was somewhat reduced due to the huge amount of suspended particulate between the site and the city. The September sampling had poor observing conditions due to atmospheric moisture. These conditions left the sky appearing dark blue, not black. Overall the sky was slightly darker at low to moderate altitudes.

The sampling session in January brought skies reminiscent of observing conditions that existed during the first sampling in March of 1995. The sky appeared black except in areas of sky glows and right along the horizon. Photometry confirmed this with very dark readings. Most of the sky was 22 magnitudes per square arcsecond or fainter. The very clear air led to a reduction in brightness of Sonoyta while allowing for an enhancement in the brightness and extent of the Phoenix glow. Comparing readings from nights with poor conditions and excellent conditions shows sky brightness at high altitudes can vary by one magnitude (250%) per square arcsecond and values associated with the upper extent of light domes can vary by even larger amounts (Table 2). This huge difference was surprising, but in retrospect it matches closely one author's (DC) amateur astronomy experience. The above result complicates the interpretation of the brightness of light pollution sources by measuring night-sky brightness.

Sampling at the Chiricahua National Monument (CHIR) confirmed the above results that sky brightness values can vary by one magnitude per square arcsecond depending on observing conditions related to atmospheric transparency (Table 3). Data were collected at a wide variety of observing sites to determine if the reduced protocol was sufficient. The following sites were chosen: Kitt Peak National Observatory, Vega-Bray Observatory, and Saguaro National Park, including both east and west districts. Isophote maps were produced which clearly showed the nature of sky brightness at the sites (Figs. 4, 5, 6, 7).

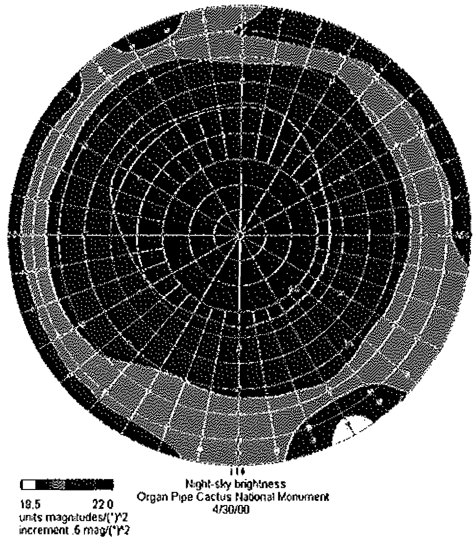

Figure 1. Organ Pipe Cactus National Monument. Night-sky brightness 04/30/00.

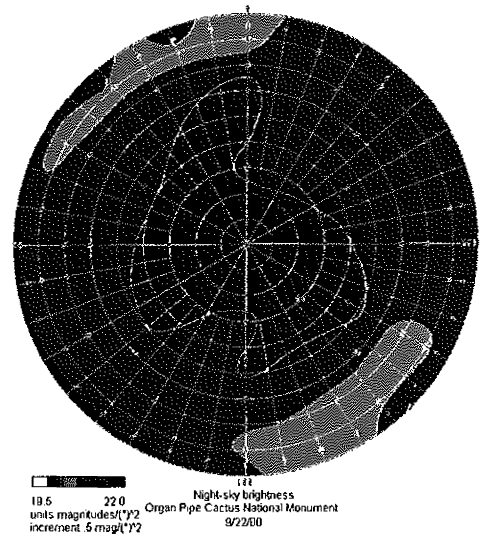

Figure 2. Organ Pipe Cactus National Monument. Night-sky brightness 09/22/00.

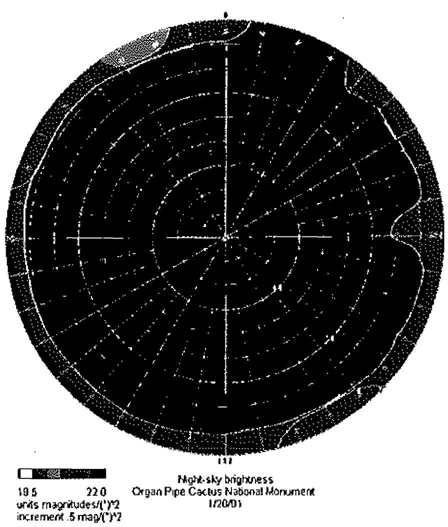

Figure 3. Organ Pipe Cactus National Monument. Night-sky brightness 01/20/01.

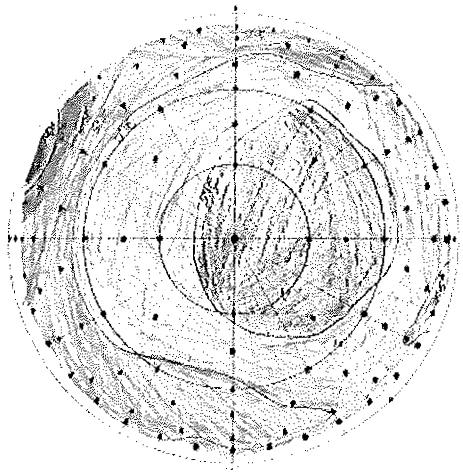

Figure 4

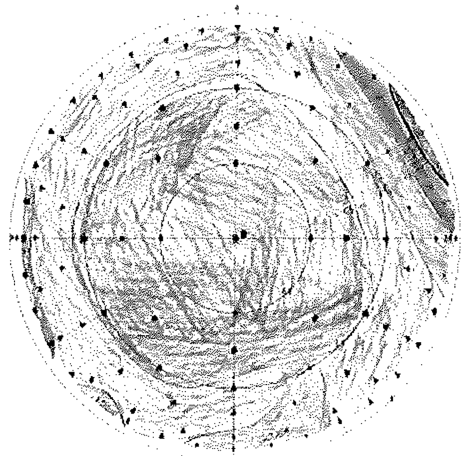

Figure 5

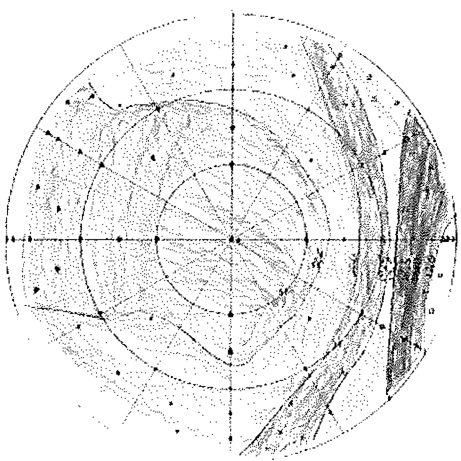

Figure 6

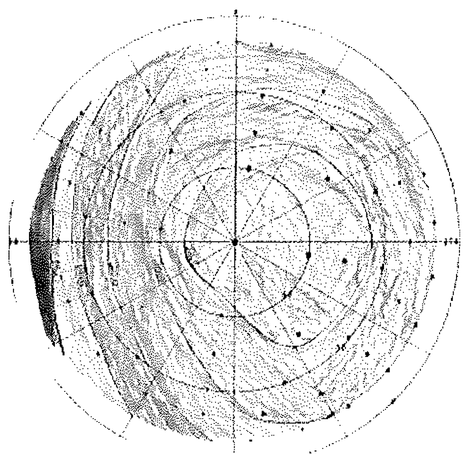

Figure 7

Figure 4. Kitt Peak National Observatory. Brightest: 18.9 mag/arcsec2; darkest: 21.9 mag/arcsec^2.

Figure 5. Vega-Bray Observatory. Brightest: 18.9 mag/arcsec^2; darkest: 21.9 mag/arcsec^2.

Figure 6. Saguaro National Park East, Douglas Springs Trail Head.

Figure 7. Saguaro National Park West, Eskiminzin Picnic Area.

Table 2. ORPI Sky Brightness Measurements

Conditions Date ALT	AZ	Bad (dust) 4/30/00 MAG/"²	Bad (moisture) 9/22/00 MAG/"²	Excellent 1/20/01 MAG/"²
5	0	20.9	20.9	21.3
5	10	20.8	20.7	21.1
5	20	20.4	20.4	20.8
5	30	20.4	20.5	20.9
5	40	20.9	21.2	21.2
5	50	21.1	Blocked	21.4
5	60	Blocked	Blocked	Blocked
5	70	Blocked	Blocked	21.4
5	80	Blocked	Blocked	Blocked
5	90	Blocked	Blocked	Blocked
5	100	21.1	21.2	21.6
5	110	21.1	21.3	21.7
5	120	Blocked	Blocked	21.8
5	130	21.1	21.4	21.8
5	140	Blocked	21.3	21.7
5	150	Blocked	21.4	21.8
5	160	Blocked	21.3	21.8
5	170	20.9	21.2	21.8
5	180	20.8	21.4	21.7
5	190	20.6	20.7	21.6
5	200	20.1	20.2	21.4
5	210	19.8	20.0	21.3
5	220	20.2	20.5	21.4
5	230	20.6	20.6	21.6
5	240	Blocked	Blocked	21.6
5	250	Blocked	Blocked	21.6
5	260	Blocked	21.2	21.5
5	270	21.1	21.2	21.5
5	280	21.1	21.1	21.6
5	290	21.0	21.1	21.7
5	300	21.0	21.2	21.9
5	310	21.1	21.2	21.9
5	320	21.1	21.2	21.8
5	330	21.2	21.2	22.0
5	340	21.2	21.1	22.0
5	350	21.0	21.0	22.0
10	0	21.0	20.9	22.1
10	20	20.8	20.9	22.0

Table 2 (continued). ORPI Sky Brightness Measurements

Conditions Date ALT	AZ	Bad (dust) 4/30/00 MAG/"²	Bad (moisture) 9/22/00 MAG/"²	Excellent 1/20/01 MAG/"²
10	60	20.9	20.9	22.1
10	80	20.8	21.0	22.2
10	100	20.9	21.1	22.3
10	120	20.8	21.2	22.3
10	140	20.9	21.2	22.3
10	160	20.8	21.1	22.5
10	180	20.7	20.9	22.4
10	200	20.4	20.5	22.2
10	220	20.4	20.5	22.2
10	240	20.7	20.7	22.3
10	260	20.8	21.0	22.0
10	280	20.9	21.1	22.0
10	300	20.8	21.1	22.0
10	320	20.9	21.1	21.9
10	340	21.0	21.1	22.0
20	0	20.9	21.2	22.2
20	30	21.0	21.2	22.1
20	60	21.0	21.1	22.1
20	90	21.0	21.2	22.1
20	120	21.0	21.3	22.3
20	150	20.9	21.3	22.0
20	180	20.9	21.1	22.3
20	210	20.8	20.9	22.0
20	240	20.9	20.9	22.1
20	270	20.9	21.0	21.9
20	300	20.9	21.1	22.1
20	330	21.0	21.3	22.0
30	0	21.3	21.5	22.3
30	45	21.3	21.3	22.4
30	90	21.3	21.3	22.3
30	135	21.1	21.4	22.2
30	180	21.1	21.3	22.5
30	225	21.1	21.2	22.2
30	270	21.1	21.2	22.0
30	315	21.1	21.5	22.1
45	0	21.5	21.6	22.4
45	60	21.5	21.4	22.5
45	120	21.4	21.5	22.4
45	180	21.3	21.5	22.4

Table 2 (continued). ORPI Sky Brightness Measurements

Conditions Date ALT	AZ	Bad (dust) 4/30/00 MAG/"2	Bad (moisture) 9/22/00 MAG/"2	Excellent 1/20/01 MAG/"2
45	240	21.3	21.5	22.4
45	300	21.4	21.4	22.3
60	0	21.7	21.4	22.5
60	90	21.7	21.5	22.5
60	180	21.5	21.4	22.4
60	270	21.5	21.5	22.4
90		21.7	21.7	22.4
90		21.7	21.7	22.4

Table 3. Comparison of two partial data sets taken at CHIR on 01/25/01 and 3/26/01. This data set shows the great variation in sky brightness due to transparency.

Conditions Date ALT	AZ	Bad Transparency 01/25/01 MAG/"2	ALT	AZ	Excellent Transparency 03/26/01 MAG/"2
5	270	20.7 Tucson			
5	310	20.8 Willcox			
5	30	21.2 low dark	5	0	22.1
20	60	21.3	0	20	22.4
30	60	21.1	0	30	22.6
30	90	21.4			
45	90	21.6	0	45	22.8
60	0	21.7	0	60	22.7
60	90	21.7			
60	180	21.6			
60	270	21.5			
90		21.8 zenith			22.7

Comparative Measurements Using a Self-Calibrating Photometer

We were able to take measurements using a single channel Pritchard photometer, a self-calibrating photometer simultaneous with measurements made with the ORPI photometer. This allowed a comparison of the measurements obtained with the two instruments. The Pritchard photometer, loaned to this project by Mr. Steven Larson of the University of Arizona, is over 30 years old, and is bulky and dependent on AC power, making remote field measurements with this instrument difficult. However, simultaneous measurements will allow newer equipment to take data in sites where sky brightness measurements with the Pritchard have been made, yet still allow the data to be compared in an reasonable manner. Also, data from the Pritchard photometer exists from the 1970's for Kitt Peak, Tumamoc Hill, and Mt. Bigelow and Mt. Lemmon in the Catalina Mountains north of Tucson (S. Larson, private communication).

Sky brightness was measured at Jarnac Observatory in Vail, Arizona, using both the Pritchard and the ORPI photometer on February 21, 2001; results from these observations are given in Table 4. All measurements were taken using an 1° aperture and using the scotopic filter built into the Pritchard. Every effort was made to ensure that there were no stars in the field, but one cannot directly see the aperture field given the Pritchard design. The dark current and zero point were reset after each five data measurements.

Figure 8 compares these two datasets. For azimuths from 0° (due north) to 90° (due east), the Pritchard measured systematically brighter skies, by up to 60%, than did the aperture photometer. For other azimuths (135° to 315°), the agreement is substantially better, with the largest difference being less than 20% (excluding the point at azimuths 135° and elevation 60°, which was apparently contaminated by a star). The zenith measurement differs by a large 30%, however.

The reason for the large difference in measured sky brightness at the zenith and in the north to east direction is not clear and is unacceptably large. These data need to be remeasured in a careful fashion.

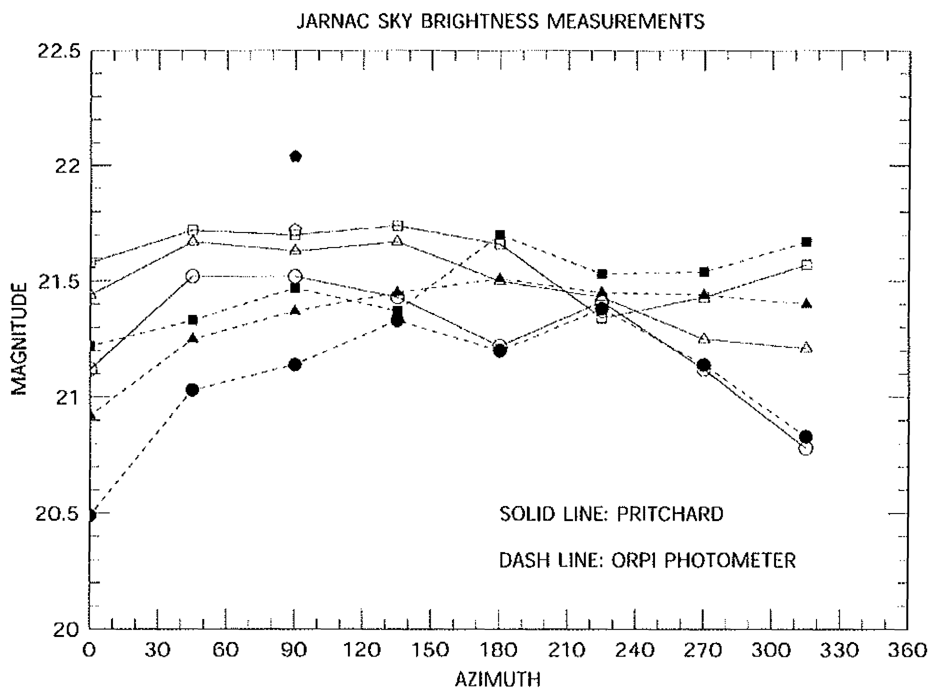

Figure 8.

Table 4. Sky Brightness Measurements:
Aperture Photometry vs. Pritchard Data

Sky brightness measurements taken at Jarnac Observatory on 02/21/01.
The Pritchard photometric output is in units of footlamberts; conversion to mag/arcsec^2 is made by using mag/sec^2 = 26.36 + 2.5 log est. (9.28 × 10^{-7} ÷ footlamberts).See IDA information sheet. Error in Pritchard measurements estimated at 1.0 × 10^{-4} footlamberts.

AZ	ALT	ORPI Aperture Photometer mag/arcsec^2	Pritchard mag/arcsec^2	Diff AP - PR (+ =) AP meas darker - = > PR meas darker
0	30	20.49	21.12	- 0.63
0	45	20.92	21.44	- 0.52
0	60	21.22	21.58	- 0.36
45	30	21.03	21.53	- 0.50
45	45	21.25	21.63	- 0.38
45	60	21.33	21.72	- 0.39
90	30	21.14	21.52	- 0.38
90	45	21.37	21.63	- 0.36
90	60	21.47	21.70	- 0.23
135	30	21.33	21.43	- 0.10
135	45	21.45	21.67	- 0.22
135	60	21.37*	21.74	- 0.37
180	30	21.20	21.22	- 0.02
180	45	21.51	21.50	+ 0.01
180	60	21.70	21.66	+ 0.07
225	30	21.38	21.41	- 0.03
225	45	21.45	21.43	+ 0.02
225	60	21.53	21.34*	+ 0.19
270	30	21.14	21.12	+ 0.02
270	45	21.44	21.25	+ 0.19
270	60	21.54	21.43	+ 0.11
315	30	20.83	20.78	+ 0.05
315	45	21.40	21.21	+ 0.19
315	60	21.67	21.57	+ 0.10
-	90	22.04	21.72	0.32

* The point marked with an asterisk is probably contaminated by a star in the aperture of the photometer.

Sky Brightness Measurements: A Wide-field CCD Experiment

Simultaneous with the Pritchard observations, CCD data was acquired with a fisheye lens attached to the CCD camera. The CCD was a model ST-8 camera produced by the Santa Barbara Instrument Group (SBIG). The CCD is based around a 1530x1020 pixel array produced by the Kodak Corporation. Attached to the camera was am 8-mm fisheye camera lens which provided a field of view of approximately 60 x 90°.

After acquisition, but prior to analysis, the CCD data is processed using a standard dark subtraction procedure. A CCD image is taken that is the same duration as the sky CCD images, however, the shutter remains closed. This will create a reference image of the fixed noise present in the CCD which can then be subtracted. This final, subtracted image is what is combined for use in the sky brightness measurement.

The individual images were 300 seconds in duration and a series of these images was taken over approximately an hour to allow stars to move to different pixels on the array due to the Earth's rotation. A total of five images was taken and later median combined in software, which effectively removed all of the stars but preserved the observed sky data.

The CCD data are reduced in the following manner. The CCD data are taken and the appropriate dark frame subtraction is performed. In order to preserve flux values, no sky flat-field calibration was performed. A small region of the field is selected that is representative of the average unvignetted sky brightness in the field. This value is given in counts per pixel. This value is multiplied by the gain of the CCD camera to get the number of photons per pixel. This is then divided by the integration time to get the number of photons per second per pixel. Calculating the area of a pixel on the sky (based on the focal length of the system) is straightforward. The sky area seen by a given pixel is then divided by the third value to get the number of photons per square arcsecond per second. The quantum efficiency of the CCD is not 100%, so the average value across the bandpass is calculated. Using the value 100/, the average Q.E. (in percent) will give a correction value for the relative sensitivity of the CCD. Multiply the number of photons per square arcsecond per second by this value to get a corrected value.

Calculate the collecting area of the optical system in square centimeters and divide the corrected flux by this value to get the number of photons per second per square centimeter per square arcsecond. The flux of the standard star Vega (mag 0) across the passband of interest is given in Tueg *et al.* (1977) and will be in the number of photons per second per square centimeter. Calculate the difference in magnitude between the two values, and the result is the sky brightness in magnitudes per square arcsecond.

For an optical system with a small field of view, calculating the area of a pixel on the sky (based on the focal length of the system) is straightforward. However, the optical system with a short focal length fisheye lens introduces significant non-linearities and distortions - basically this system projects most of the hemisphere (the sky) onto a plane (the CCD detector).

To determine how much sky each pixel was seeing, data were taken with the CCD and fisheye lens combination and using a uniformly illuminated planetarium dome at Flandrau Planetarium at the University of Arizona as an integration sphere. That data show that there are large scale variations in sensitivity of the system that cannot fully be accounted for. When those images are applied to the sky images to attempt to correct the data for those uniformities (a flat field calibration, in essence), variations greater than those originally present are apparent. It is possible that the illumination was not entirely uniform in the course of this experiment, exaggerating the effect of the variations that may be present. An examination of this problem is in progress.

Further CCD tests are planned in an attempt to characterize the usefulness of this type of system for night sky brightness monitoring.

Equipment Considerations

Several equipment-related issues came up during data collection for this project. The first is the use of the laptop computer in field data collection. At dark sites the brightness of the red filtered screen interferes with the dark adaptation of the data collector. This prohibits simultaneous use of the photometer and the computer. This problem could be eliminated with the addition of one more field personnel. The battery for the laptop only allows 45 minutes of use. This is not enough time to complete data collection. This problem could be solved with the use of automotive 12-volt adapter and a long (25 feet) cord. Other equipment considerations involve power as well. The battery pack failed on two occasions. One time (November 28) it was insufficiently charged. A built-in voltmeter on the battery pack would solve this problem. The other time at CHIR on January 25, extreme cold (15 degrees) caused irregular power output that led to false readings until the battery had equilibrated. Conversely the operator's performance became less effective as he equilibrated. These power problems could be solve with a 12-volt automotive adapter and a long power cord. The operator's problem could be solved with a snowmobile suit and a parka.

Zero point calibration of the photometer is a problem that was noted in 1995 by DC. The data that the photometer gives for sky patch brightness is consistently too low. This indicates that the diaphragm aperture is smaller that the assumed one millimeter in diameter. Chad Moore also ran into this problem and he contacted Optec to find a solution. Optec offered to replace the existing aperture with a precision laser cut aperture for around $100. This could be done for the ORPI photometer and the current aperture should be carefully measured under magnification to determine its true diameter. Once the actual diameter is known, all data collected thus far can be adjusted.

Conclusions

The reduced observing protocol defined in this project allows full-sky brightness measurements at a given location to be made in approximately three hours. A systematic measurement program can be established without requiring personnel to shift to a full-night observing schedule.

The large variation in sky brightness arising from atmospheric dust requires careful selection of observing nights in order to clearly separate light pollution effects from natural variations in sky brightness.

The simultaneous measurements using the ORPI telescope/photometric system and the Pritchard photometer gave a surprisingly large difference of up to 60% (Figure 8). Also, the large area CCD measurements did not yield conclusive results. Further work is needed to understand these differences or to further simplify the observing protocol.

Recommendations

Protecting the quality of night skies is an important goal of resource management for the National Park Service (The Vanishing Skies,1999). ORPI has been a leader in establishing a program to quantify the quality of its dark skies and to identify steps than can be taken to protect them. It is recommended that the effort continues through the following steps:

1. Continue the program of regular sky brightness measurements.
2. Work with the International Dark-sky Association and other national parks to improve the measurement methodology. An all-sky CCD camera system should be considered as a shared resource among several elements of the NPS.
3. Establish a program to reduce light pollution with ORPI.
4. Establish an outreach program to educate surrounding communities as to the importance of reducing light pollution through good lighting partnerships.

References

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