The Digital Blue Sky at Night

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Rayleigh-scattered moonlight creates a blue sky at night, but our eyes are not sensitive enough to perceive the color. With the help of a digital camera, however, the vivid shade of the evening sky can come alive to anyone.

Nearly a decade ago, I wrote an OPN article about using manual film cameras to capture the blue color of the night sky, which is caused by Rayleigh-scattered moonlight (November 1996, *Optics & Photonics News*, "What Color Is the Night Sky?," p. 54). In recent years, I have been asked whether digital cameras can be used for the same purpose. My initial experiments convinced me that the digital approach works well; in fact, as I delved deeper, I learned that digital images require shorter exposure times than film.

Where does the blue go?

At visible wavelengths, moonlight is simply reflected sunlight, and the lunar reflectance is quite flat with wavelength. Although it doesn't appear so to us, a clear sky under a full moon is blue for the same reason it is in the daytime: because of Rayleigh scattering—the scattering of light by molecules in the air. (See box on p. 22, What Is Rayleigh Scattering?).

Why, then, does the night sky appear black? Moonlight, which is about 463,000 times weaker than sunlight, is not bright enough to stimulate our color vision. The human retina contains two types of photoreceptor cells: rods, which are sensitive to dim light but not color, and cones, which are finely tuned for

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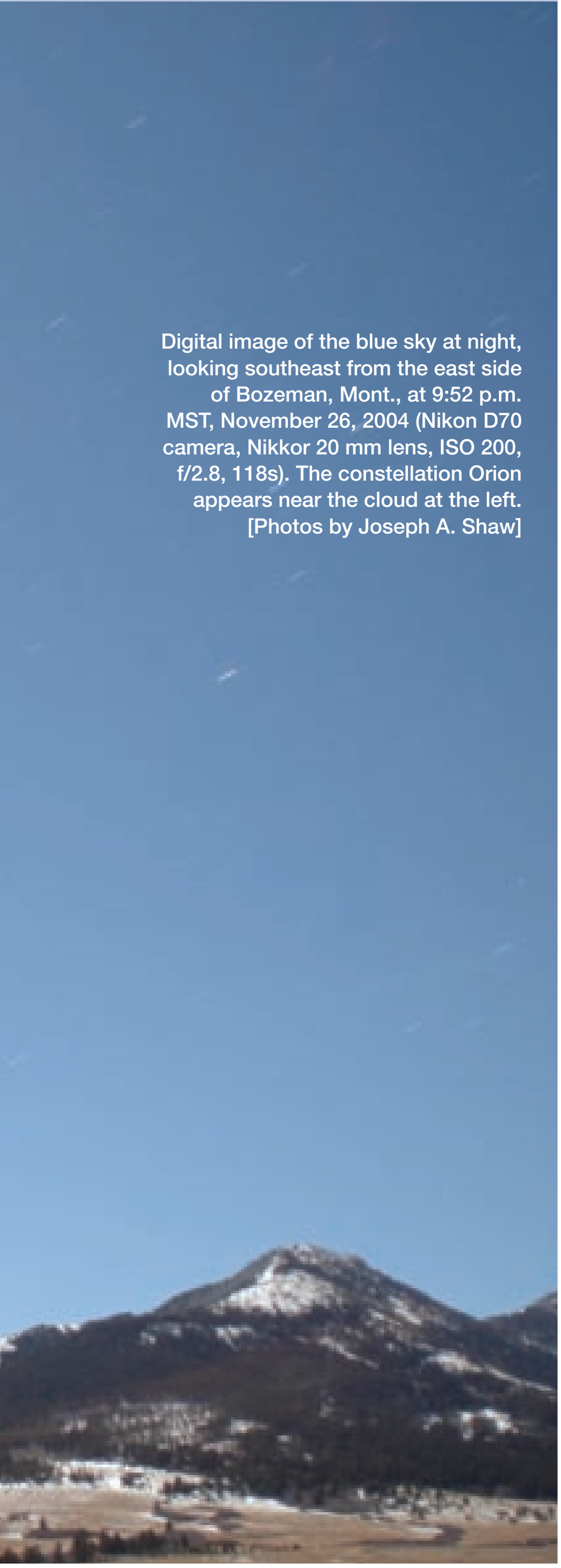

Digital image of the blue sky at night, looking southeast from the east side of Bozeman, Mont., at 9:52 p.m. MST, November 26, 2004 (Nikon D70 camera, Nikkor 20 mm lens, ISO 200, f/2.8, 118s). The constellation Orion appears near the cloud at the left. [Photos by Joseph A. Shaw]

color vision but not bright light. Thus, our eyes make a tradeoff between high-sensitivity black-and-white vision (with rods) and lower-sensitivity color vision (with cones).

Fortunately, a camera can do what our eyes cannot: It can integrate the scattered light for a long enough time to record a nighttime image of a rich blue sky that looks as if it had been taken during the day.

Sunlight vs. moonlight

By comparing the relative brightness of sunlight to moonlight, a photographer can approximate the exposure time required to capture the blue color of the night sky. With both sunlight and moonlight, the initial source of light is the sun; the moon simply serves as an intermediate reflector at night. Therefore, to estimate the difference in brightness, it is necessary to examine how the moon reflects sunlight. All other variables—including the solar spectrum, atmospheric transmittance, etc.—are essentially common to sunlight and moonlight.

The sun-moon distance is essentially the same as the sun-Earth distance. Thus, for both Earth and the moon, we can conveniently use the same number for the projected solid angle subtended by the sun. A ratio of the cross-sectional area of the sun to the square of the sun-moon distance gives this projected solid angle as $\Omega_s = 6.8 \times 10^{-5}$ sr. Solar irradiance (W/m^2) on the Earth or the moon is calculated by multiplying solar radiance (W/m^2 sr) by this projected solid angle. The lunar surface reflects solar irradiance with an approximately Lambertian reflectance of $R_m = 0.1$ at visible wavelengths.

Therefore, the radiance of the full moon can be found by multiplying the incident solar irradiance by 0.1 and dividing by π. The reflected irradiance is converted to radiance by dividing by π, which is the projected solid angle of the hemisphere into which the Lambertian surface scatters sunlight. The resulting estimate is that lunar radiance is less than solar radiance by a factor of $(\Omega_s/\pi)R_m = 2.16 \times 10^{-6}$. The Modtran radiative transfer code yields a very similar number—2.33×10^{-6}.

Photographing the blue sky at night

To account for the weaker light of the moon, the exposure time for a photograph of a nighttime scene should be longer than that required for a sunlit setting by approximately $1/(2.16 \times 10^{-6}) = 4.63 \times 10^5$. For example, if a daytime photograph of the blue sky requires an exposure of 1/1000 s at an aperture size of f/5.6, the nighttime blue sky should require an exposure time of 463 s (about 8 min) at the same f-number.

Achieving a properly exposed image with this longer exposure time requires that the imaging system be made linear over many orders of magnitude—something that film sometimes fails to do. This shortcoming of film—called reciprocity failure—translates into a reduction of sensitivity at long exposure times (also possibly a color shift).

Our calculation generates the expected exposure times listed in the table below, based on an exposure meter reading of 1/1000 s at f/5.6 for the daytime blue sky imaged with ISO 200 film or digital sensitivity setting. (My film and digital camera meters both give the same reading.) The actual value of this "reference" daytime exposure varies depending on the sun's angle, atmospheric aerosol content, and so forth, but the table nevertheless provides a good starting point.

f-number	Time
2.8	116 s (~ 2 min)
4	232 s (~ 4 min)
5.6	463 s (~ 8 min)
8	926 s (~ 16 min)

Theoretical exposures for a clear blue night sky at ISO 200 based on a daytime reading of 1/1000 s at f/5.6.

Note that each f-number listed in the table differs by a factor of the square root of two. This difference is called one "stop." Each stop changes the amount of light collected by a factor of two. The optical power collected by an imaging system can be found by multiplying the scene radiance by the system throughput, or AΩ product.

This value is usually calculated as the product of the entrance-pupil area

Digital image of the blue sky at night, looking north at 11:39 p.m. MDT on July 23, 2005 (Nikon D70 camera, Nikkor 20 mm lens, ISO 400, f/2.8, 180 s). Contrast is less than in the image on p. 18 because of extra scattering of city lights by forest fire smoke.

and the image-plane projected solid angle—which is determined as the ratio of film or detector area to the square of the focal length for a focus at infinity. For an imaging system with a circular pupil, the throughput can be expressed as

$$A\Omega = \frac{\pi A_d}{4(f/\#)^2} \quad ,$$

where A_d is the detector area.

Therefore, for a system that is linear with detected optical power, the required exposure time doubles for a one-stop increase in f-number. Similarly, the exposure time is halved for every two-fold increase of ISO (i.e., the “116 s at f/2.8” exposure becomes “58 s at f/2.8” when the ISO is changed from 200 to 400).

Going digital …

When I first tried to capture the blue night sky with early compact digital cameras, the results were OK, but certainly did not convince me to give up my film SLR cameras. Some of the problems that I encountered were optically slow lenses and the occurrence of the troublesome digital noise that tends to accumulate in a charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) detector during long exposure times.

Astronomers have taken stunning photographs with CCD cameras for years, but the consumer-grade cameras that I was using did not have cooled detectors or anywhere near the sensitivity of astronomical-grade imagers. These days, however, digital SLR cameras are available that provide low enough noise and good enough noise-reduction algorithms to provide spectacular results. Compact digital cameras are getting better too, although they still tend to have optically slow lenses and often do not provide adequate manual control.

The photo on the opening spread is one of the first pictures I took of a moonlit scene with my Nikon D70 digital SLR camera. I shot the photo facing southeast toward the mountains that lie between Bozeman, Mont., and Yellowstone National Park at 9:52 p.m. (Mountain Standard Time, MST) on November 26, 2004, right at full moon.

With the moon located just above the image’s field of view, the photo suffers from lens flare that could have been corrected by using a lens hood. Nevertheless, this image is a pretty good example of the blue sky at night. It looks just like a daytime scene until you notice the constellation Orion near the cloud at the left. The streaky cloud image also provides evidence of a long exposure.

Taking this picture was easy. All I did was set the camera on a tripod with a 20-mm lens, turn on the noise-reduction mode, and open the shutter for 118 s at f/2.8 and ISO 200. (The theoretical exposure time from the reference table is 116 s.) I used an infrared remote control to open and close the shutter with the camera in “bulb” mode.

As I admired this image on the camera’s LCD screen, I thought fondly of the many hours I had spent with my film camera, blindly shooting dozens of pictures with progressively longer exposure times to figure out which ones worked best. Guided by the digital camera’s LCD screen, even a person with no photography experience could dial in the proper settings much more rapidly than I had done with film.

One of the first things I noticed when photographing the night sky with digital cameras is that the images seemed to require shorter exposure times than those shot with film cameras. Entries in my photo notebook confirmed that there were systematic differences of up to a

Slide film image corresponding to image at left (Nikon FM2 camera, Sigma 28 mm lens, same exposure). The underexposure by at least one stop relative to the digital image to the left/right seems to be caused by film reciprocity failure.

A reference daytime photograph of the same scene, taken at 10:00 a.m. MDT on Aug. 20, 2005 (Nikon D70 camera, Nikkor 20 mm lens, ISO 200, f/2.8, 1/4000 s).

factor of two for long exposures, but there were too many variables to quantify the differences without making a direct comparison.

Digital vs. film

Thus, in July and August 2005, I set out to spend several nights around the full moon to simultaneously photograph a moonlit scene with film and digital cameras. I found that the digital camera did indeed require a shorter exposure time than film. Exposures differed by about one-half to one stop with several-minute to tens-of-minute exposures.

One possible explanation is that near-infrared light exposes digital images faster, since CCDs are much more sensitive at these wavelengths than normal film. However, if this had been a significant factor contributing to the shorter exposures, I would have expected the images to look stranger than they did, since vegetation is unusually bright in the near infrared. Moreover, the detectors in these cameras have a filter that blocks most of the near-infrared light.

Nevertheless, I discovered by accident that, in low-light conditions, my camera still detects some of the near-infrared remote control beam. One night, I kept noticing that blurry, UFO-looking red blobs were appearing in my Milky Way images until I started pointing the shutter remote control away from the lens more carefully. (The beam cannot be seen easily in daytime pictures.)

Although the integration of residual near-infrared light may speed up the exposure a little on the digital camera, I am not convinced that this is a major factor. Instead, it appears that film reciprocity failure is the primary culprit—mainly because the exposure differences seem to grow with exposure time.

The two photos above left and center were taken simultaneously from a digital and film camera, respectively. The first digital picture (*above left on p. 20*) is significantly brighter than the film picture, which has been scanned carefully in an attempt to retain the original exposure. These pictures were taken near the end of my film-digital comparison experiment near midnight (Mountain Daylight Time, MDT) on July 23, 2005, two days after full moon. I shot these images looking down a narrow draw in a plateau just east of Bozeman, facing north toward the Bridger Mountains. This is the location of a hiking trail that wraps around the east side of my neighborhood.

For the experiment, I used a 28-mm lens on a Nikon FM2 camera loaded with slide film and a 20-mm lens on a Nikon D70 digital camera to approximately compensate for the 1.5× smaller size of the CCD relative to 35-mm film. Both pictures are 180-s exposures at f/2.8 and ISO 400. I estimate that the film image is at least one full stop underexposed relative to the digital image. (The film image best matches the mean of digital images taken with 90-s and 60-s exposures just a few minutes earlier.) Film reciprocity failure is the most likely cause.

Actual vs. theoretical exposures

Quantifying differences between film and digital pictures is difficult at best: Scanned film images are subject to user-adjustable scanner settings, leaving it up to our eyes to judge between slides and digital images displayed on a calibrated monitor. Measuring variations among digital images, on the other hand, is much easier because digital cameras can display histograms—graphs that display the distribution of brightness levels in a scene.

As a reference for digital image comparisons, I used the histogram for the daytime image shown in the figure at right, whose exposure exactly matches the

[What Is Rayleigh Scattering?]

In 1871, John W. Strutt, the third Baron Rayleigh (usually referred to simply as Lord Rayleigh), showed that the scattering of light by small particles varies as the inverse fourth power of wavelength ($1/\lambda^4$). Due to this inverse dependence on wavelength, air molecules in the Earth's atmosphere scatter about 4-5 times more short-wavelength blue light than longer-wavelength red light. In 1899, Rayleigh identified atmospheric molecules as a sufficient source of scattering to explain the blue sky.

Rayleigh scattering theory applies to dipoles. In other words, it is independent of particle shape and relevant only to particles that are much smaller than the wavelength of light, such as atmospheric gas molecules. Much larger aerosols and dust particles require a higher-order theory, such as Mie scattering, which is applicable to spheres.

daytime in the reference table on p. 19 (Aug. 20, 2005, 10:00 a.m. MDT, ISO 200, f/2.8, 1/4000 s). The histogram for this picture revealed a fairly uniform distribution of pixels, with digital numbers mostly between 100 and 200 (the full range of 8-bit images is 0-255).

Using the daytime reference image makes it possible to sort through a set of digital images with different exposures to find the one that best approximates daytime, thereby comparing actual and theoretical night-sky exposures. This process led to the selection of the image shown on p. 20 (*left*) as the best day-like exposure from that night. However, the exposure of 180 s at f/2.8 and ISO 400 is about three times longer than the theoretical value of 58 s from the table on p. 19 (for f/2.8 and ISO 400). What accounts for the discrepancy?

First off, the difference is not as dramatic as it might initially appear. That's because the exposure time must be changed by a factor of two to accomplish significantly different photographic exposures. Still, there is something very interesting causing this picture to require such a long exposure compared with the theoretical value.

By taking pictures on several nights during August 2005, I confirmed that those taken exactly at full moon (e.g., Aug. 19) are consistently one-quarter to one-half stop brighter than those taken with identical exposures two nights following a full moon (e.g., Aug. 21). The cause is apparently the strong retro-reflective character of the lunar surface (the "lunar opposition" effect).

In reality, moonlight is much brighter at full moon than would be expected from considering the illuminated area at full moon relative to just before or after. However, the Lambertian assumption that we made for the lunar surface does not take this into account. To verify the significance of this effect, I found a comparable histogram from an image on Aug. 19, 2005, right at full moon, which had a 92-s exposure at f/2.8 and ISO 400 (half the exposure time of the photo on p. 20).

Another potentially significant factor, which I ignored when calculating the theoretical moonlight exposure, is the different zenith angle of the moon and sun. The moon is lower in the sky during summer in the northern hemisphere than it is during winter, while the summer sun is higher. Although the earlier calculation assumed that the effect of the atmosphere was the same for sunlight and moonlight, this difference in zenith angle could increase the required summertime night-sky exposures by about one-quarter to possibly one-half stop. Thus, it appears that the combination of the lunar opposition effect and the greater atmospheric extinction for a lower moon in summer accounts for my observations.

The photo at right (p. 23) shows the same scene as the previous three photographs (on pp. 20-1), but is in a vertical format and was taken with a longer exposure time. It was shot on August 21, 2005, at 1:33 a.m. MDT at ISO 200, f/5.6. Exposure time is 963 s (16 min)—about twice the theoretical value from the reference table.

The picture was taken one night after a full moon, and thus the lunar opposition effect may contribute slightly to the longer exposure, as does the lower moon angle. Vertical images also require longer exposures because of the extra time it takes to achieve day-like imaging high in the sky versus at the horizon. In this longer exposure, star streaks begin to form circular paths around Polaris—the North Star.

Which approach is better?

Both digital cameras and film cameras have advantages and drawbacks. Digital cameras offer many features that make this kind of photography easier and more enjoyable than film. I love the instant feedback that my digital camera provides as well as its excellent technical capabilities. However, working with my old film camera reminded me how much I love its "feel" and its incredibly large and bright viewfinder. I hope that future digital SLR cameras will have viewfinders as good as the one on my old FM2.

My film camera also operates without a battery, which is an enormous advantage in cold weather. Nevertheless, the rechargeable batteries used in digital cameras have a long life, and I always keep a charged spare with me. Another significant advantage of digital cameras is that you do not have to take as many notes, because each digital image is stored with complete data about the camera and lens settings.

One thing I dislike about my digital camera, however, is that the noise-reduction algorithm requires processing time equal to the exposure time. For a 1-min exposure, this is not so bad, but waiting 20 min for a 10-min exposure can be really annoying. Some cameras have faster noise-reduction processing, and I hope that most others will soon be improved in this regard.

This kind of photography can be quite useful for measuring clouds and haze at night, as well as for teaching radiometry and optical detection. Not to mention how fun it is to view something in a photograph that your own eyes cannot see. To capture the digital blue sky at night for yourself, you'll need a camera with fully manual capability that includes a bulb setting, a tripod and, of course, a full moon. Good luck! ◭

Acknowledgments

My digital exploration of the night sky has been encouraged by questions from Prof. C.F. Bohren (Penn State) and numerous slide-show attendees and students, and by discussions with my father, Prof. G.E. Shaw (University of Alaska). I originally got the idea of photographing the blue sky at night from Robert Greenler's book, *Rainbows, Halos, and Glories*.

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[References and Resources]

- >> J.N. Howard, "John William Strutt, third Baron Rayleigh," Appl. Opt. **3**, 1091-101 (1964).
- >> R. Greenler, *Rainbows, Halos, and Glories*, Cambridge, U.K.: Cambridge Univ. Press (1980).
- >> C.F. Bohren and D.R. Huffman, Absorption and scattering of light by small particles, New York: John Wiley and Sons (1983).
- >> J.A. Shaw, "What color is the night sky?," Optics & Photonics News **7** (11), 54-5 (1996).
- >> J.A. Shaw, "Modeling infrared lunar radiance," Opt. Eng. **38** (10), 1763-4 (1999).

Vertical nighttime photograph taken at 01:33 a.m., Aug. 21, 2005 (Nikon D70 camera, Nikkor 20 mm lens, ISO 200, f/5.6, 963 s).