A Simple, Portable Apparatus to Measure Night Sky Brightness at Various Zenith Angles

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Abstract We describe a simple apparatus for making measurements of night sky brightness as a function of zenith and azimuth using "off-the-shelf" equipment: a Unihedron Sky Quality Meter with Lens, a protractor with plumb-line, a tripod, and a hand-held compass. Compared to a photoelectric or CCD photometric system, this apparatus is simple to set up and use and does not require complex data reduction procedures. Thus, this apparatus makes measurements of night sky brightness as a function of zenith and azimuthal angles quite amenable to students.

1. Introduction

The natural brightness of the night sky originates predominantly from the integrated light of faint stars within our own galaxy, airglow, and zodiacal light (e.g. Leinert *et al.* 1998). Other sources include starlight scattered by interstellar dust which produces a diffuse glow along the galactic plane and a weak contribution from extragalactic light (Leinert and Mattila 1998). Airglow, the visible emission produced when atmospheric atoms and molecules (e.g. O, Na, O_2) previously excited by ultraviolet solar radiation during the day decay, is the dominant source of night sky brightness (Benn and Ellision 2010). Airglow increases with zenith angle due to the thicker air column along the line of sight. Zodiacal light, sunlight scattered by interplanetary dust, is the second largest contributor to night sky brightness and increases towards the ecliptic. The third major contribution to night sky brightness results from the integrated light of stars not individually accounted for; this is strongest toward the galactic equator and decreases toward the galactic poles (e.g. Leinert and Mattila 1998).

Garstang (1989) developed a detailed model for the natural sky background in the context of a larger study to predict the brightness of the night sky caused by a city. At zenith, the faint star and galaxy light contributes about 40 percent to the total night sky brightness while airglow contributes the remaining 60 percent (Garstang 1989); Garstang's model is consistent with earlier photometric observations (e.g. Pike 1976, Berry 1976): natural night sky brightness at sea level increases by some 0.5 mag/arcsec^2 from zenith to 85° zenith angle primarily due to increased airglow. Measurements of actual night sky brightness as a function of zenith angle can be compared to the Gargstang model of natural night sky brightness. Such measurements can serve as a useful quantitative measure of light pollution at a given location.

A number of methods can be used to measure the brightness of the night sky as a function of both zenith and azimuth. Upgren (1991) used multiple, naked eye observations of bright stars to determine changes in night sky brightness near the horizon over a period of 14 years. This method has the distinct advantage of being simple and cheap but such measurements will also be somewhat subjective, varying from observer to observer. Portable, wide-field CCD systems have been successfully employed (e.g. Cinzano and Falchi 2003; Duriscoe *et al.* 2007) to record mosaic images of night sky brightness from zenith to horizon in all azimuth angles. Such systems have the advantages of being fast, quantitative, and repeatable, however, neither the data reduction process nor the cost (roughly $15,000 U.S.) is trivial. More recently, several authors have experimented with DSLR systems equipped with a "fish-eye" lens (Zotti 2007). Such systems are relatively inexpensive, roughly $1,000 for a modest DSLR camera, and can obtain an image of nearly the whole sky in a single image. These systems can also give calibrated data with a high degree of accuracy, however, the data reduction and analysis of such images is still rather complex.

The advent of inexpensive, hand-held sky quality light meters presents another opportunity to "map" night sky brightness as a function of zenith angle and azimuth. The Unihedron Sky Quality Meter with lens, hereafter the SQM-L, was originally designed to take measurements at zenith. However, the fairly narrow observation cone of this device allows one to measure sky brightness at angles well below zenith. The SQM-L allows users to make simple, reliable measurements of the night sky in the visible region of the spectrum in only a few seconds. It has already been incorporated into the Globe-at-Night observing campaign in America (Walker 2010). We report on our use of the SQM-L as part of a simple, inexpensive apparatus to measure night sky brightness as a function of zenith angle and altitude. This apparatus improves and simplifies night sky brightness measurements using the SQM-L in two respects: 1) previously this device was designed for zenith only measurements; our setup allows observers to make measurements at various zenith angles, and 2) mounting the device on a tripod ensures that the device is always pointed in the same direction, increasing the accuracy of any individual measurement as compared to simply holding the device by hand.

2. Apparatus and measurement method

The core of our apparatus is the Unihedron SQM-L. The SQM-L is nearly identical to its predecessor the SQM; both devices are equipped with the same light sensor (the TAOS TSL237S) and the same infrared blocking filter (a HOYA CM-500). Each device is a small (3.6 × 2.6 × 1.1 in.), portable light meter powered by a 9-volt battery. Both the SQM and the SQM-L are equipped with an infrared blocking filter and measure only visible light (from red to blue). Both devices measure the ambient temperature and all photometric measurements are automatically corrected for temperature effects. Measurement with either device requires a few seconds in heavily light polluted areas to no more than 80 seconds under the darkest skies. Each individual SQM/SQM-L device is calibrated using a NIST-traceable light meter. The Unihedron Corporation reports the precision of ±0.10 mag/arcsec^2 for measurements made with a single device; this precision is consistent with field observations (e.g. Craine *et al.* 2008; Smith *et al.* 2008). For a full report of the performance characteristics of the SQM, see Cinzano 2005.

The main difference between the SQM and SQM-L is the field of view. The SQM has a full-cone width of 84 degrees while the SQM-L is fitted with a lens which reduces the full-cone width to 20 degrees. The addition of the lens means that zenith measurements taken with the SQM-L are not affected by lights or shading on the horizon. The smaller field of view also makes the SQM-L useful for making measurements of sky brightness at various zenith angles, whereas the SQM is really only useful for zenith measurements.

Our apparatus is shown in Figure 1. The SQM-L is mounted on the shoe pad of a tripod using a wide rubber band. One must take care to avoid placing the rubber band on or near the sensor lens. Velcro tape is used to mount a protractor (equipped with a plumb-line) along the side of the SQM-L; this allows us to measure zenith angles. A compass is used to determine the direction in which the device points. The total cost of the device is under $250 US; the most expensive components of the device are the SQM-L ($135 US) and a sturdy tripod ($100 U.S.).

Before proceeding to take measurements, it is necessary confirm that the night sky is clear. This can be achieved by examining both infrared and water vapor satellite images; such images are available from the National Oceanic and Atmospheric Administration website (NASA 2010) at:

http://www.weather.gov/sat_tab.php?image=ir.

In infrared satellite images, high altitude clouds appear bright. However, low altitude clouds and fog are similar in temperature to the ground and hence infrared images will not be useful for identifying these. Low altitude clouds and fog can be identified using a new product, the GEOS 4-km shortwave albedo IR4 cloud images, available at:

http://rammb.cira.colostate.edu/ramsdis/online/goes-west_goes-east.asp.

Measurements were taken at two different sites on July 15, 2010; on this date the Moon age was 3.0 days. Measurements were taken after the Moon set. Measurements were taken at zenith angle zero and then at zenith angles of 0°, 20°, 40°, 60°, and 80°. At each particular zenith angle, five individual measurements were taken and then averaged. A compass was used to establish the cardinal directions for each set of azimuthal data. Here, we note that one must take care to correct for the magnetic “declination” of a given observation site; magnetic “declination” is the angle between geographic north pole and the magnetic pole and varies with latitude. The magnetic declination of a site can be quite large and this should be determined prior to making measurements in the field by consulting a good topographical map or consulting a magnetic "declination" calculator (e.g. see the National Oceanic and Atmospheric Administration's Geophysical Data Center www.ngdc.noaa.gov/geomagmodels/struts/calcDeclination).

All data were recorded by hand using a notebook, pen, and flashlight. However, it should be noted that the Unihedron Corporation does offer a SQM-L with USB connectivity ($189.99 US). The "SQM-LU" allows for continual, connected measurements of sky brightness. It comes supplied with a USB cable and applications for reading data in Perl.

3. Results

Using a standard spreadsheet program, we plot our brightness measurements in magnitudes per square arcsecond as a function of zenith angle. Observations along each of the four major cardinal lines serve as a measure of azimuth. (Note that here we are measuring brightness in a fairly specific direction. If one wishes to document sky glow along the horizon due to distant cities, this can be achieved by closer spacing of each azimuth reading, about every 20 degrees or so; this would require the use of a mounted compass or a second protractor mounted horizontally on the SQM-L.) From a previous study (Birriel, Wheatley, and McMichael 2010) we identified two sites of interest for our study: Cave Run Lake near Morehead, Kentucky, which serves as our local "dark-sky" site with a zenith SQM-L reading of 21.7 mag/arcsec^2, and a location at the edge of the Morehead State University Campus near Eagle Lake with a SQM-L zenith reading of 19.3 mag/arcsec^2.

In both cases, we compare our readings to the Garstang (1989) model of the dark sky site for Mount Graham Junipero Serra Peak in Boulder, Colorado; this model is for a moonless night at solar minimum in the photometric *V* band. Cinzano (2005) found a slight mismatch between the SQM-L spectral response and the Johnson *V* band. He determined that SQM readings can be converted to *V* band readings via the simple expression $V = \text{SQM} - 0.17$. We have made this adjustment to all our measured values.

The Cave Run Lake and Morehead sites are in Rowan County, Kentucky, nestled in the foothills of the central Appalachian Mountains. The region is characterized by largely forested, hilly, and highly dissected terrain with elevation ranging between 208 m and 404 m. The Cave Run Lake site is about 20 kilometers from the town of Morehead and is effectively shielded from much of the light from town. Readings taken with our device at the Cave Run Lake site are shown in Figure 2. One feature that immediately stands out on this plot are the small differences (±0.1 to ±0.2 mag/arcsec^2) between individual azimuth measurements; these results are well within the expected precision of the SQM-L. The overall dependence of sky brightness on zenith angle is close to what is predicted by the Garstang model, although the curves are systematically shifted upward with respect to a true dark-sky site at solar minimum. Given that our measurements were taken shortly after solar minimum (NASA 2010), this most likely arises simply from elevated light levels due to artificial light sources. This site does exhibit a systematic brightening near the horizon in the southerly directions due to the presence of a light from the nearby dam reflecting off the lake. In the opposite direction, the decline in brightness near the horizon results from the presence of hills towards the north.

The Eagle Lake site is located in the town of Morehead. It is located at the northern edge of the Morehead State University campus at the crest of a hill. The campus and town extend to the south while north lies the Daniel Boone National Forest. As seen in Figure 3, the brightness of the sky increases dramatically looking toward the southerly direction of town and campus. In fact, the presence of artificial lighting is clearly evidenced by the rapid increase in brightness.

4. Summary and future

The results obtained with our apparatus show that one can document night sky brightness as a function of both zenith angle and azimuth without expensive equipment. Measurements can be obtained quickly and results easily analyzed. This makes the apparatus a particularly useful tool for experimental projects at both the high school and college levels. We envision employing this apparatus as a laboratory tool for undergraduate astronomy and physics courses. In addition, measurements from such a device should prove valuable for science fair projects and college student research projects on light pollution. We also plan to use this device to evaluate Walker's law (Walker 1973), taking measurements of sky brightness at a zenith angle of 45 degrees at various distances from nearby large cities.

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Figure 1a. Mounting the SQM-L on the tripod shoe pad can be done quite simply and quickly with the use of a thick rubber band.

Figure 1b. To measure zenith angles, we attached a simple protractor with plumb-line to the side of the SQM using adhesive Velcro tape.

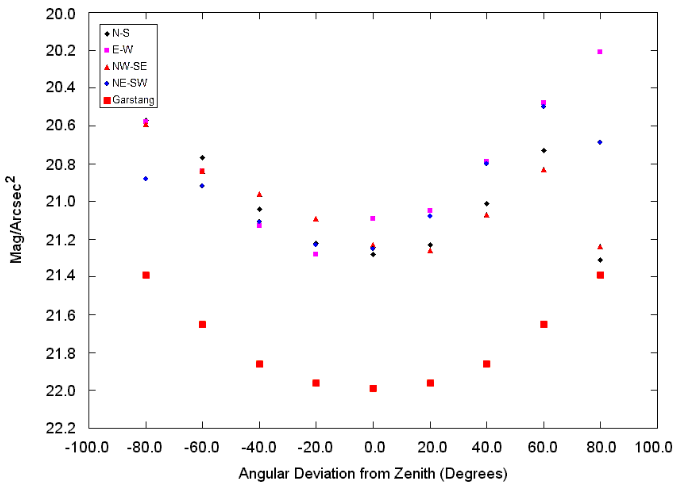

Figure 2a. A plot of night sky brightness in mag/arcsec2 as a function of zenith angle and azimuth for the Cave Run Lake site. Zenith angles pointing North along the N-S line and East along the E-W line are positive. Zenith angles along the NE-SW line are positive when point NE and along the NW-SE line the angles are positive when pointing NW. The Garstang model for natural night sky brightness is also plotted. The ±0.2 mag/arcsec2 uncertainty in the SQM-L device is clearly visible in readings near zenith.

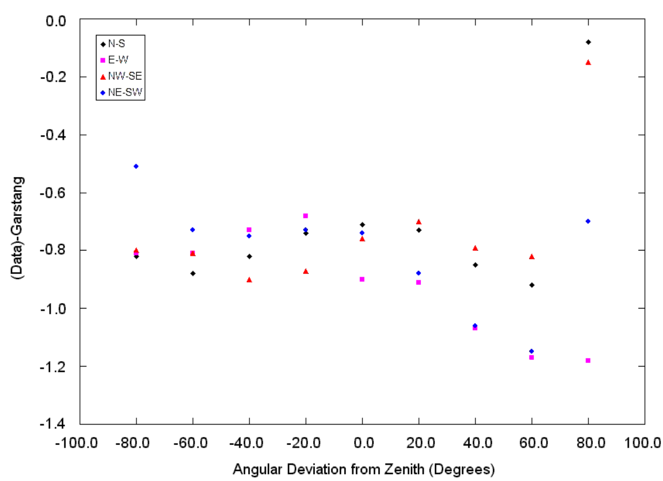

Figure 2b. The difference between the observed sky brightness (at Cave Run Lake) and the Garstang model. Note that sky brightness at this site is comparatively low, with an increase in brightness at zenith of less than one magnitude.

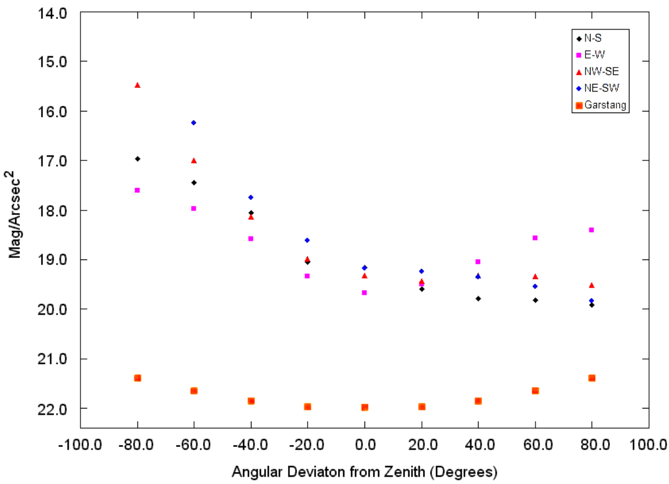

Figure 3a. A plot of night sky brightness in mag/arcsec^2 as a function of zenith angle and azimuth for the Eagle Lake site at the edge of the Morehead State University campus.

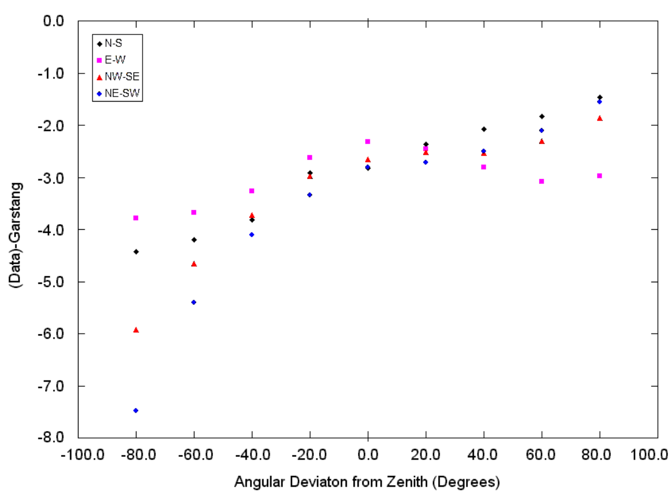

Figure 3b. The observed sky brightness (at Eagle Lake) minus the Garstang model. Notice that this site exhibits significant light pollution with an excess brightness of 3.0 mag/arcsec^2 at zenith and increasing excess brightness at off-zenith angles.