Analysis of Seven Years of Globe at Night Data

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Abstract The Globe at Night (GaN) project website contains seven years of night-sky brightness data contributed by citizen scientists. We perform a statistical analysis of naked-eye limiting magnitudes (NELMs) and find that over the period from 2006 to 2012 global averages of NELMs have remained essentially constant. Observations in which participants reported both NELM and Unihedron Sky Quality Meter (SQM) measurements are compared to a theoretical expression relating night sky surface brightness and NELM: the overall agreement between observed and predicted NELM values based on the reported SQM measurements supports the reliability of GaN data.

1. The Globe at Night (GaN) project

The faint band of the Milky Way as seen under a dark sky is very much a part of humanity's cultural and natural heritage. More than one-fifth of the world population, two-thirds of the United States population, and one-half of the European Union population have already lost naked-eye visibility of the Milky Way (Cinzano *et al.* 2001). This loss is caused by light pollution. Light pollution is artificial night sky brightness, directed up toward the sky and wasted. The International Dark-Sky Association estimates that one-third of outdoor lighting escapes unused into space, causing light pollution (IDA 2012). Under an unpolluted sky we ought to see a few thousand stars, yet we see only a couple hundred from most suburban areas. Light pollution is a serious and growing issue that impacts astronomical research, the economy, ecology, energy conservation, human health, public safety, and our shared ability to see the night sky. For this reason, the National Optical Astronomy Observatory has taken a lead in promoting activities on dark skies awareness by getting people worldwide involved in programs like the Globe at Night campaign (GaN 2013, http://www.globeatnight.org).

The campaign is easy and fun to do. First, you match the appearance of the campaign's constellation (Orion in the January, February, and March campaign and Leo in the March and April campaign, and so on) with simple star maps of progressively fainter stars. If you have a handheld, digital sky brightness meter known as a "Sky Quality Meter" or SQM (Unihedron 2013, http://www.unihedron.com/projects/darksky/), you have an opportunity to take more precise measurements of the night sky. With either or both of these measurements, you then submit them online, including the date, time, and location of your observation. If people have smart mobile phones or tablets, they can submit their measurements in real time. To do this, you can use the web application at www.globeatnight.org/webapp/. With smart phones and tablets, the location, date, and time are put in automatically. And if you do not have a smart phone or tablet, there are user-friendly tools on the Globe at Night report page to find latitude and longitude.

After all the campaign's measurements are submitted, the project's organizers release a map of light-pollution levels worldwide. Over the first seven annual campaigns, volunteers from more than 115 nations contributed 83,000 measurements. The data can be downloaded from www.globeatnight.org/analyze.html for comparisons with a variety of other data sets. (For an example, see this article's summary.) The formats for the GaN data files include csv, text, excel, (Google) kmz, ESRI geodatabase, and shape files.

2. Theoretical background

Night sky brightness as observed from the ground can be measured via a variety of methods. Semi-quantitative measures use the binocular vision of the unaided human eye: these include the naked-eye limiting magnitude, the Bortle Scale (Bortle 2001), and the visibility of the Milky Way (Moore 2001). All of these methods depend to some degree on observer age, visual acuity, and experience. Quantitative measures of night sky surface brightness include photographic or CCD photometry. The newly developed Unihedron Sky Quality Meter (SQM) is a portable, hand-held photometric device about the size of a deck of cards that contains a small CCD chip and on-board processor. The SQM is an extremely portable and inexpensive (less than $150) device designed to take quick and accurate (±0.10 magnitudes per square arcsecond) measurements of night sky surface brightness. Globe at Night participants can submit either naked-eye limiting magnitude (NELM) measurements or a combination of NELM and SQM measurements. (There are two models of SQM: the original model which has a FOV of ±40 degrees at FWHM, and the SQM-L which is equipped with a lens that reduces the FOV to ±10 degrees FWHM. The latter is primarily used now and is best used in cities where most of the Globe data come from.)

A theoretical relationship between naked-eye limiting magnitudes and night sky surface brightness was developed by Schaefer (1990) from empirical curves derived by Knoll *et al.* (1946). The relationship converted from Schaefer's equations 2, 16, and 17 is given by

$$\mathrm{NELM} = 7.93 - 5{*}\log(10^{(4.316 - (B/5))} + 1), \tag{1}$$

where B is the sky brightness in magnitudes per square arcsecond and NELM is simply the naked-eye limiting magnitude. This expression assumes binocular vision, natural pupils, and no atmospheric absorption; in addition, the observer was free to pick her/his own point of fixation. This relationship is utilized in the sky brightness nomogram on the Dark Skies Awareness (2011) website (http://www.darkskiesawareness.org/nomogram.php). Below, we will use Equation 1 as to evaluate the reliability of GaN data.

3. Statistical analysis of GaN data

One simple approach to using the Globe at Night data involves looking at global trends in NELMs over time. We might expect an overall increase in light pollution globally with increased industrialization or a decrease resulting from light pollution abatement programs in Europe and the Americas (for example, Dick (2000, 2010); Smith *et al.* (2006); Zitelli *et al.* (2001). Using a spread-sheet program, we plotted the relative frequencies of NELMs 1 through 7 from 2006 until 2012 (Figure 1). The general shape and centroid of each histogram varies slightly from year to year, but the centroids are clustered around 3–4. In any given year, the vast majority of measured naked eye limiting magnitudes lie between 3 and 5. Given that participants must choose which of the seven charts best fit her/his view of a given constellation, the uncertainty in measurements is, at best, ±0.5 magnitude and likely as high as ±1 magnitude. One could argue that the small changes observed in relative frequencies of NELM from 2006 to 2012 result from observational uncertainties and not from any real change in global NELMs. In an alternative approach, we plot all the NELM data from 2006 to 2012 on the same chart (Figure 2). Looking at the individual NELMS, it appears that there is a general upward trend in reported NELMs 1 through 3, indicating that more observers were seeing brighter skies. The opposite appears to be true of NELMs 4 through 7: there appears to be a general downward trend in the number of observers reporting dark skies. One interpretation is it that skies have gotten brighter over the six years of GaN campaign, but is this really the case?

Statistical analysis of the data is easily done using a spread sheet. In Table 1, we summarize the descriptive statistics of the data for each year: counts (that is, the number of observations), mean, standard deviation, standard error, five

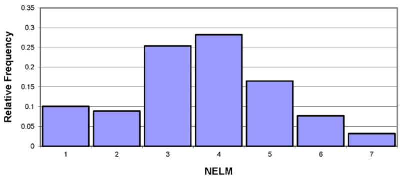

Figure 1a. 2006 frequency historgram.

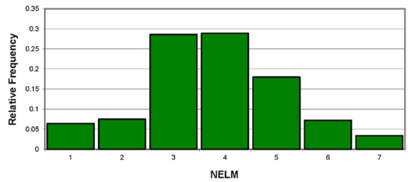

Figure 1b. 2007 frequency historgram.

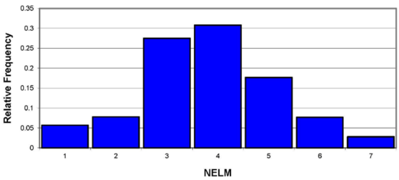

Figure 1c. 2008 frequency histogram.

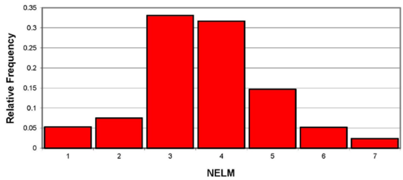

Figure 1d. 2009 frequency histogram.

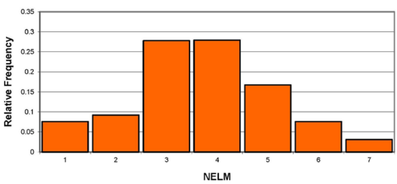

Figure 1e. 2010 frequency histogram.

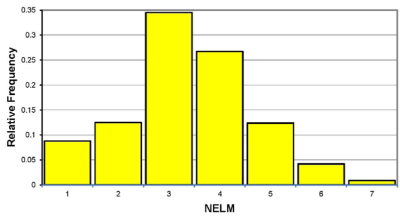

Figure 1f. 2011 frequency histogram.

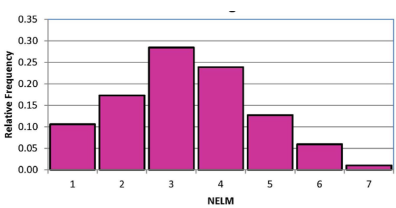

Figure 1g. 2012 frequency histogram.

Figure 1a–g. Frequency histograms of naked eye limiting magnitudes (NELMs) for Globe at Night data over the years 2006–2012. Given a reasonable uncertainty of ±1.0 associated with determining a matching chart for a given constellation, it appears that globally there has been no significant change in night sky brightness over the last six years.

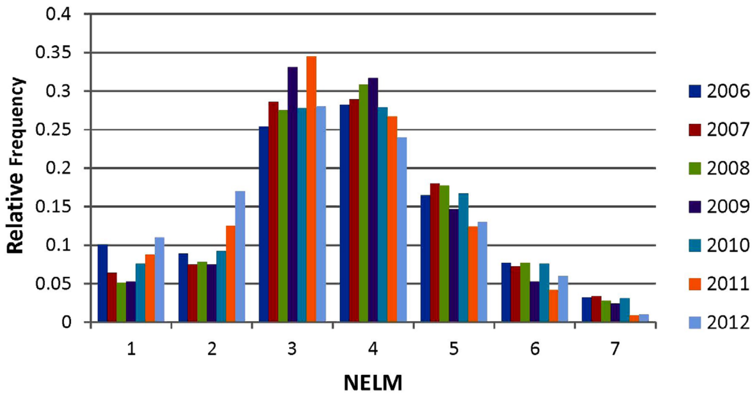

Figure 2. Naked-eye limiting magnitudes (NELMs) reported over the seven-year period of the Globe at Night project. Individual NELMs are plotted together and color coded by year. It appears that NELMs 1–3 exhibit a general upward slope, indicating that a larger fraction of observers reported brighter skies. NELMs 4–7, indicative of darker skies, appear to exhibit a general downward trend, indicating that a smaller fraction of participants reported darker skies.

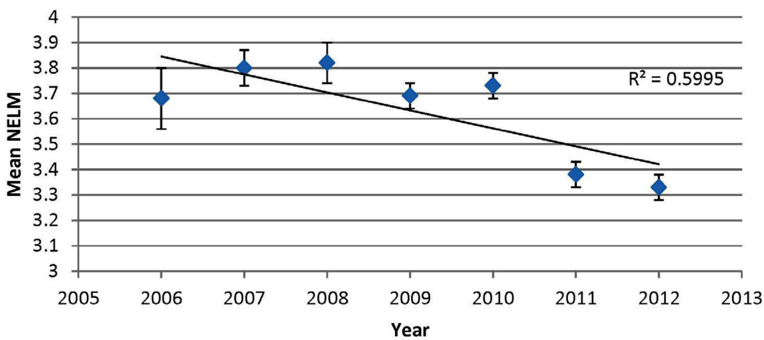

Figure 3. Mean global naked-eye limiting magnitudes (NELMs) reported over the seven-year period of the Globe at Night project. The error bars represent the five sigma confidence levels found in Table 1. A linear fit to the GaN data shows a weak trend toward brighter skies.

Table 1. Globe at Night NELM statistics.

Year	*Counts*	*Mean*	*Standard Deviation*	*Standard Error*	*5 Sigma Confidence*	*Skewness*
2006	3990	3.68	1.47	0.02	0.06	0.02
2007	7261	3.80	1.38	0.02	0.07	0.08
2008	5295	3.82	1.34	0.02	0.08	0.05
2009	14063	3.69	1.26	0.01	0.05	0.20
2010	14394	3.73	1.42	0.01	0.05	0.08
2011	12461	3.38	1.27	0.01	0.05	0.12
2012	14896	3.33	1.39	0.01	0.05	0.21

sigma confidence level, and skewness. The means are all relatively close and the data all exhibit a very small, but similar, skew. The mean NELM has remained relatively constant over the duration of the GaN project: for the first five years the mean has essentially remained constant at about 3.74 but in the last two years the average has dropped slightly to 3.36 (Figure 3).

Figure 3 exhibits a slight downward trend, indicating an overall brightening of skies over time. In keeping with a study of North America night sky brightness from 1947–2000 (Cinzano 2003) which determined that night sky brightness increased linearly over this period of time, we also adopt a linear fit to the GaN average NELM. However, with a correlation coefficient, that is, R^2, of 0.60 this corresponds to a 15 percent probability (Taylor 1997) that our seven NELM data points are uncorrelated with time. Therefore, we cannot argue conclusively that our skies are getting brighter. If we perform a one-tailed hypothesis test for the slope of the regression line, the null hypothesis is that the slope is zero and the alternative hypothesis is that the slope is less than zero; these correspond to the global average NELM being constant with time and decreasing with time, respectively. Using a spreadsheet to perform a regression analysis, the probability of the linear regression is 4.1%. Thus, we can reject the null hypothesis at the two sigma level but at the more rigorous three sigma level, we fail to reject the null hypothesis. We conclude that the global NELM appears to be constant over the seven years of Globe at Night campaigns.

According to urbanization data from the United Nations Department of Economics and Social Affairs (2013), there continues to be a world-wide trend toward urbanization. Over the period of the GaN project, this trend is strong in North America, South America, and Europe (http://esa.un.org/unup/Analytical-Figures/Fig_6.htm). If more Globe at Night observers are reporting from urban areas, the constant NELM values over time might actually be a sign of progress, in that we are not adding additional lighting to accommodate the increase in population in urban areas. This is an important question that future analyses of Globe at Night data may help answer as more data are added.

4. Observational errors: testing the reliability of GaN data

Many citizen science projects have individuals collecting data with little or no specialized scientific training. Most of these have been in the areas of biology and environmental studies (e.g. Rosales and Montan 2010, and references therein). In astronomy, the American Association of Variable Star Observers has led the promotion of public participation in the collection and reporting of astronomical data. Data collected by citizen volunteers have several advantages: they generally cover a larger geographic area, span a longer period of time, and are free. There has always been some concern regarding the quality of citizen science data. Fortunately, most studies show that well-trained volunteers do provide very reliable data (see, for example, Sachs *et al.* 2007; Alabri 2010; Malatesta *et al.* 2006; Cohn 2008).

How can we test the reliability of the Globe at Night data? Individual observations that include both a NELM and an SQM observation can be compared to the theoretical relationship in Equation 1. A couple of issues arose in the course of studying the reliability of the data that necessitated a "data filtering" stage. First, it was expected as part of the Globe at Night protocol that observers reporting SQM values were also to provide a simultaneous NELM value. This did not always happen: some SQM values were provided without a simultaneous NELM observation. To assess this, we removed all data that did not include both SQM and NELM values. In addition, sometimes the reported SQM and NELM values were grossly inconsistent; we used the sky brightness nomogram provided on the Dark Skies Awareness (2011) website (http://www.darkskiesawareness.org/nomogram.php) to remove data points that were clearly subject to high observational inaccuracy. An example of such a data point is a reported NELM of 2 when the SQM value is well above 19, indicating that the SQM reading was subject to either pointing error or shading due to buildings. In other instances, observers reported SQM values below 14 with NELM values well above the 0.5 expected from the sky brightness nomogram; this is likely the result of using an SQM too close to a nearby source of artificial light. The elimination rates for these apparent SQM pointing errors were between 1 and 3% for 2007 through 2010 and also in 2012. In 2011, the elimination rate was 9%. This relatively low elimination rate indicates at least nine out of ten SQM users appear to be using these devices correctly.

To test the reliability of the Globe at Night NELM data, we inserted the reported SQM values into Equation (1) and calculated the "expected" NELM value. We then plotted a frequency distribution of observed minus expected NELM values for all years of data from 2007 to 2012 (as per Schaefer 1990); the total number of data points was 6081. A histogram of the differences between observed and predicted NELMs based on reported SQM values is presented in Figure 4.

The histogram is essentially Gaussian in shape with a centroid of about –0.25 magnitude and a half-width-at half-maximum of about –1.0 magnitude. This half-width-at half-maximum is consistent with what we would expect for a reasonable limit on the uncertainty in observed NELM for an inexperienced observer. Note that a positive error value indicates that the observer saw fainter than expected based on the model, while a negative error indicates that the observer saw brighter than predicted.

We compared our results with that of Schaefer (1990), who developed a formula (which is different from Equation 1) for predicting telescopic limiting magnitudes based on zenith brightness. His group of 314 observations from 1990 shows a very similar qualitative distribution before correcting for observer experience. The centroid of his distribution is –0.24 with a half-width-half-

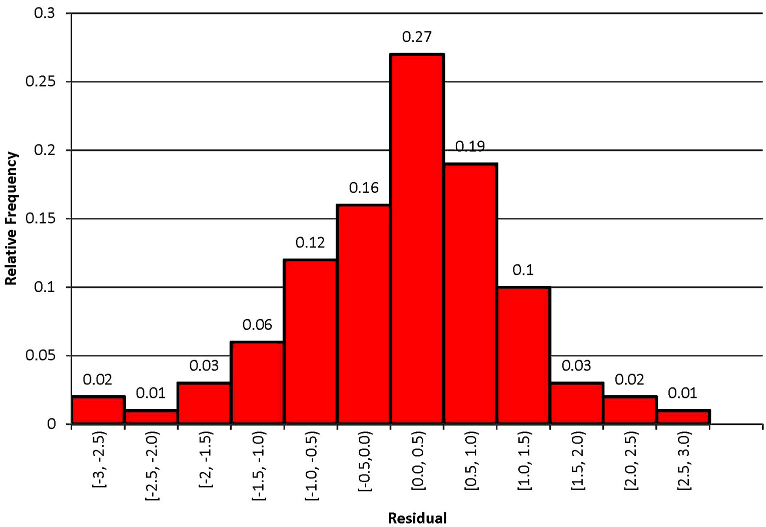

Figure 4. A histogram showing the distribution of observational errors for Globe at Night data. We plot observed minus predicted NELM values for 4,198 measured pairs of night sky bright using sky quality meters (in magnitudes per square arcsecond at zenith) and naked-eye limiting magnitudes for a given constellation (Orion, Leo, or Crux). The predicted values are calculated using Equation (1). A positive error value indicates that the observer saw fainter than expected. The histogram is roughly Gaussian in shape with a centroid of about –0.25 magnitude and a half-width-at half-maximum of about –1.0 magnitude.

maximum of 0.75. Schaefer's model was compared with 53 observations found in the astronomical literature, 17 observations made by himself and another professional astronomer, and 244 observations from a group of individuals who responded to a questionnaire Schaefer published in *Sky & Telescope* magazine. This group is therefore likely much more experienced than the GaN participants. The close agreement between Schaefer's distribution of errors and the GaN distribution is a good indicator that the GaN participants are submitting reliable data. Further support for the reliability of GaN data is the fact that the average GaN NELM correlates strongly with the light emitted upward as measured by the Defense Meteorological Satellite Program Operational Linescan System and with estimates of the World Atlas of Artificial Night SkyBrightness for European and North American skyglow (Kyba *et al.* 2013).

One interesting property of our distribution of errors is that the data appear to be weighted more on the side of positive errors than negative errors. In fact, for every positive error bin, the frequency is slightly higher than the corresponding negative error bin. Schaefer (1990) asked his participants to rate their experience level on a scale of 1 to 9 and was able to correct for observer experience. He found that more experienced observers tended to see fainter than less experienced observers. In fact, a very experienced observer might see a full magnitude fainter than an inexperienced observer. This could mean GaN observers tend to be a bit more optimistic and overestimate their NELMs. Alternatively, only about 6,000 of the total 62,682 reported observations have provided SQM values with corresponding NELMs. SQMs range in price from $120 to $135 plus taxes (U.S.) so, perhaps the group reporting SQM values represents a group of more experienced amateur astronomers and school teachers. GaN does not request information on observer experience, so at this point we do not have enough information to discriminate between these two possibilities.

5. Summary

The Globe at Night project was designed to increase public awareness of light pollution by having citizen-scientists around the world observe and report measured night sky brightness. It has evolved into a database of reliable measurements as demonstrated above. Our analysis of NELM data might seem to suggest that we have made little progress in decreasing light pollution on a global scale. On the other hand, the continuing urbanization of the global population with a nearly constant mean NELM seems to suggest some progress: we have not increased urban lighting to accommodate the additional urban inhabitants! Alternatively, perhaps we have simply gotten better at directing our light downward (Kyba et al. 2013). Determining the success of local or regional light pollution abatement projects will require a more sophisticated method of filtering data based on either identification of a city name or a restriction on the geographic coordinates.

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