Teaching Illumination Engineering Using Light Pollution Education Kits

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ABSTRACT

One-third of outdoor lighting escapes unused into space, causing light pollution. Light pollution is a growing concern on many fronts: energy conservation, cost, safety, health, effects on wildlife, and our ability to view the stars. How we use illumination engineering to optimize where, when, and how light is used is of significant importance. We will discuss how NOAO's light pollution education kits are used to teach illumination engineering. In particular we will address topics associated with achieving sufficient ground coverage, color rendition, types of outdoor lighting, glare and sky glow, assessment of city lights, and task-oriented lighting.

Keywords: illumination engineering, light pollution, energy consumption

1. INTRODUCTION

1.1 Light Pollution as a Tool to Teach About Illumination Engineering

Application of proper illumination engineering principles is key to responsible outdoor lighting. Task-oriented lighting optimizes why, where, when, and how lights are placed. Opportunities to learn concepts in illumination engineering are typically introduced at the college level[1], with topics such as photopic and scotopic vision, nighttime visibility, color rendering, reflectance and scattering models, Lambertian surfaces, uniform ground illumination, different sources of illumination, and exterior lighting design.[2,3,4]

To plant the seed at an earlier age[5,6,7], the National Optical Astronomy Observatory (NOAO), in collaboration with the International Dark-Sky Association (IDA), has developed teaching resources for students in grades 3-12. The IDA estimates that one-third of outdoor lighting escapes unused into space, causing light pollution. Light pollution is artificial night sky brightness, directed up toward the sky and wasted. With half of the world's population now living in cities, light pollution is a growing concern on many fronts: energy consumption, cost, safety, health, and effects on wildlife, as well as our ability to view the stars. In this paper, we will discuss how NOAO's light pollution education kit is being used to raise public awareness of these issues through proper illumination engineering. The kit includes tools to participate in the night sky light pollution monitoring campaign "GLOBE at Night", a light shielding demonstration, and a set of activities on how to perform an outdoor lighting audit.

1.2 Illumination Engineering as a Tool to Teach About Light Pollution

Over-illumination due to artificial outdoor lighting can incur substantial costs. Typically 20 to 50 percent of the total energy used in homes and offices goes toward lighting. For some buildings over 90 percent of the lighting energy is wasted through over-illumination. A single 100 W light bulb used just 6 hours a day can cost over $26 per year (assuming US$0.12/kWh). With the increasing number of streetlights, big box stores and billboards, outdoor lighting is a critical component of energy use today. Several strategies to minimize energy requirements and achieve an energy-responsive design can be considered:

- Specification of illumination requirements for each given area.
- Analysis of lighting quality to ensure that adverse components of lighting (for example, glare or incorrect color spectrum) are not biasing the design.
- Integration of space planning and exterior architecture (including choice of exterior surfaces and area geometries) to lighting design.
- Design of time of night use that does not expend unnecessary energy.

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- Selection of fixture and lamp types that reflect best available technology for energy conservation.
- Training of building occupants to use lighting equipment in most efficient manner.
- Maintenance of lighting systems to minimize energy waste.

By following these guidelines an illumination engineer can achieve the goals of implementing a community responsive design, with minimum light pollution and light trespass. These guidelines are used to design the contents of the light pollution kit to enable young students to get inside to understand better illumination engineering.

1.3 The Approach

The NOAO staff has constructed a carefully crafted, focused, sequential, cumulative set of 3 learning experiences that introduce students in grades 5 through 12 to the energy-responsive design principles. The first of the three learning experiences is the light shielding demonstration. It provides a visual illustration of the causes of light pollution and the main vocabulary that relates to illumination engineering. The second learning experience is the school outdoor lighting audit, which has students perform an audit and produce a revised master plan by retrofitting with compliant lighting. They then report on their results to a school board or city council. The solutions rely on an understanding of illumination engineering principles. The third learning experience is an introduction to the GLOBE at Night light pollution assessment campaign. GLOBE at Night provides an opportunity for more global awareness of the importance of remedying light pollution issues, using illumination engineering as a main solution. The three learning experiences can stand alone educationally, but together they provide an integrated learning unit.

2. THE LIGHT POLLUTION KIT

2.1 Overview

The light pollution kit is designed to support the three learning experiences and includes various materials to teach about light pollution and illumination engineering. The contents include:

- 1 Sky Quality Meter
- 1 children's book "There Once Was a Sky Full of Stars" by B. Crelin
- various instructional handouts
- 2 DVD set: "Let There Be Night"
- 1 CD on activities for Dark Skies Rangers Activities Program
- 1 poster & a bookmark
- 1 GLOBE at Night postcard
- 1 set of trading cards on light pollution
- 1 flashlight with batteries and a red balloon
- 2 mini-flashlights with batteries
- 1 white paper cube with holes (i.e., mini-planetarium: assembly needed using black tape)
- 1 painted PVC cap (i.e., light shield)
- 2 toy figurines + a set of 2 mats of city streets

Figure 1. The light pollution kit

The light shielding demonstration is a centerpiece of the kit and is described later (section 3), as is the Sky Quality Meter or "SQM" (section 5). The other kit ingredients include a CD with ancillary materials to help carry out the GLOBE at Night program: teacher packets, activities, brochures on the effects of light pollution on energy, safety, health and wildlife, a PowerPoint presentation, and certificates of program completion. A poster titled "Our GLOBE at Night" poster is a great visual aid on light pollution. It shows a composite view of the entire Earth taken at night, illustrating the light emanating from cities, transportation routes, and even fishing vessels using lights to attract squid. The postcards are for advertising the GLOBE at Night event. The two DVDs have a planetarium show that has stand-alone segments and other valuable ancillary materials on dark skies awareness. The flashlight with the red balloon, used in outdoor activities, is an inexpensive way to reduce light levels and keep eyes dark-adapted to enjoy the night sky.

Figure 2. The light shielding demonstration (on the left) and the Sky Quality Meter (on the right).

3. THE LIGHT SHIELDING DEMONSTRATION

3.1 Overview

The light shielding demonstration (www.darkskiesawareness.org/DarkSkiesRangers/) interactively illustrates how shielding can reduce the three main types of light pollution while at the same time making lighting more effective for task-oriented activities, and efficient in terms of safety, cost and energy conservation. All the materials needed for the demonstration are provided in the Light Pollution Education Kit or can be easily obtained if the kit is not available.

3.2 PowerPoint Presentation: Three Main Types of Light Pollution

The PowerPoint presentation on the CD in the kit is designed to stimulate a healthy discussion on the three main types of light pollution. Glare is too much background light. It usually comes in the form of a bright light shining directly in the eyes that interferes with the visual task at hand. To demonstrate glare, students are asked if they can see the stop sign or read the important sign below it in Figure 3. Light trespass is light that spills into an area where it is unwanted. Students are asked whether they would be able to sleep if light from the neighbor's yard trespassed into their bedroom window shown in Figure 3. Sky glow is when light scatters or reflects off particles in the air, giving the appearance of a glowing sky.[8] Students are asked if they see any stars in Figure 3.

The main types of light pollution offer a good segue to a discussion of quality lighting. It can be explained that quality lighting maximizes the ability to gain visual information and has the desired visual effects, like good vision and good night ambiance, while minimizing the adverse effects like energy waste, glare, light trespass and sky glow. Keys to quality lighting include shining the light down onto the object that needs to be illuminated, seeing the illuminated objects of interest rather than the source (e.g., no glare), lighting only when and where needed, and not over-lighting. It also includes using energy efficient lighting sources.

Figure 3. Examples of a) glare (Can you see the stop sign or read the sign below it?), b) light trespass (Would you be able to sleep if your bedroom window faced this neighbor's light?) and c) sky glow (Can you see any stars?).

3.3 The Interactive Demonstration

The light shielding demonstration provides a hands-on opportunity to witness the main effects of light pollution, namely glare, light trespass and sky glow. It also shows how with proper shielding of light sources these effects can be minimized. The demonstration is conducted in a very dark room with a high ceiling, if possible. The kit includes a special flat floor mat that represents a city. To model a city a simple toy floor mat of city streets and different business buildings scaled for matchbox cars is used. One can use one "mini-light" (included in the kit) as a streetlight by taking off the reflector. With the reflector removed, the small bulb of the mini-light approximates a point source. In this "candle mode", light goes in all directions and creates glare. Two 1.5-inch tall toy figurines of people (included) are placed under the unshielded light.

A special backdrop and a "mini-planetarium" are also used to enhance the interactive demonstration. As part of the kit, Bob Crelin's illustrations in his book "There Once was a Sky Full of Stars" are used as the backdrop to create a more realistic street scene. The mini-planetarium included in the kit is a 4-inch paper cube with holes for stars on one side and an opening for the second mini-light (in candle mode) on the opposite side. With the room lights off, you turn on the mini-flashlight in candle mode for the planetarium and place it barely inside the cube, allowing stars to be projected onto the ceiling. By turning on the "streetlight", participants notice instances of glare, sky glow, and light trespass into people's homes. The people under the streetlight, for instance, can barely be seen. To minimize these effects you can demonstrate how a simple shield, in this case a PVC cap, could help by covering the top of the "streetlight". When the cap is used, more light goes down to the street and the glare is blocked.

During the demonstration a discussion can ensue about the differences noticed with and without the shield, for instance, with respect to glare. How does using a shield improve light trespass into your bedroom window next door to the light? How is your view of the stars affected (e.g., sky glow)? How does the lighting of the area directly under the lamp change? If more of the light is directed where you want it (i.e., task-oriented lighting), the conditions for safety and security can be improved. Also with a shielded lamp, if more light is directed downward where you need it, a lower wattage lamp can be used, which reduces energy consumption and cost.

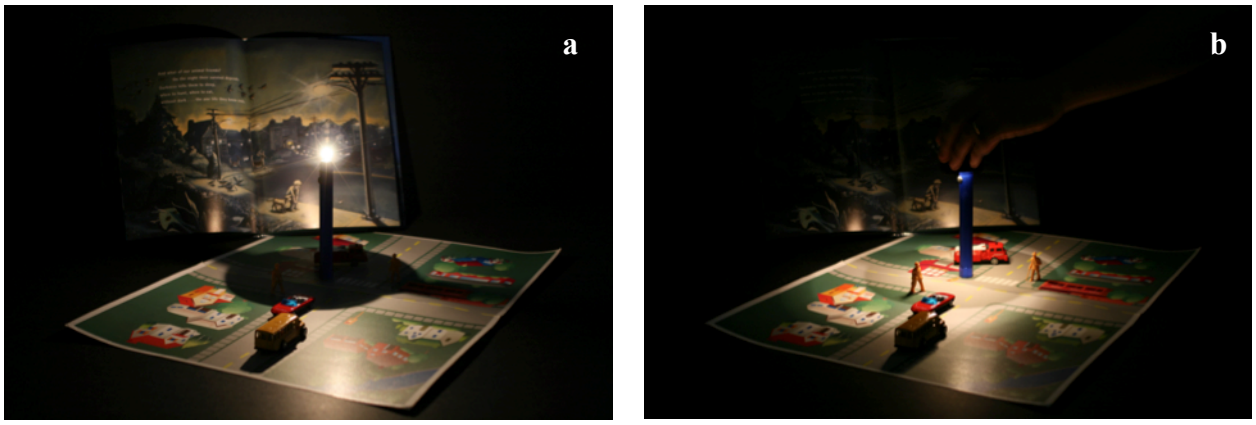

Figure 4. The light shielding demonstration in action, without the shield (left) and with the shield (right). What differences are noticed?

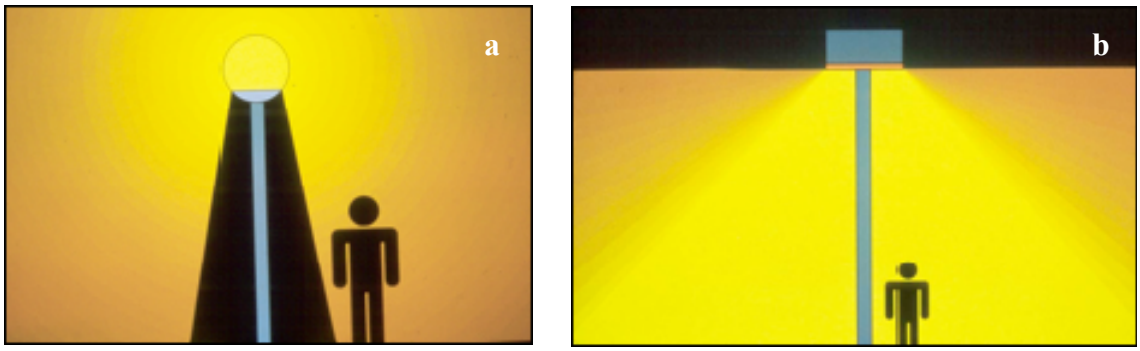

Figure 5. Examples of bad and good lighting. Figure 5a illustrates a globe light, lighting everywhere but not always where it's needed. Figure 5b illustrates a shielded light where the light is directed downward where it is needed and not upward where it would be wasted. (image credit: IDA)

4. SCHOOL OUTDOOR LIGHTING AUDIT

4.1 Overview

The school outdoor lighting audit is a set of four activities designed to provide a teaching tool for secondary school students who would like to learn more about quality outdoor lighting. In preparation, a PowerPoint presentation provides reference material to support the activities. The activities include: becoming familiar with the vocabulary, participating in an energy lighting audit, making measurements and observations for the audit, and producing a revised master plan. The activities increase in complexity as the student/audience progresses through them. The activities culminate with students investigating the appropriate lighting to replace the existing fixtures and lamps. Beside a lighting retrofit, this could include a redesign. Lighting engineers first think about why they want to light an area, where they want to light, when they want to light, at and what illumination level they want to light. They also consider what kind of light they need to use, picking the most appropriate lamp for the task, including the spectral characteristics of the lamp. A redesign

might even change the entire configuration of where lights are placed. Based upon the choices researched, the students then calculate the new energy expenditure. The difference between the current situation and the proposed plan can then be explored. As a result, a recommended plan of action can be proposed to the school board or city council.

4.2 Goals and Learning Objectives

The first goal of the School Outdoor Lighting Audit (www.darkskiesawareness.org/DarkSkiesRangers/) is to provide students with tools and information they need to effectively monitor energy use within their campus or neighborhood. Second, the goal is to identify ways to save money by using energy wisely. Third, the audit helps them to understand the environmental implications of their choices. Fourth, it encourages municipalities, schools, and businesses to consider managing or retrofitting their buildings so that energy is used as efficiently and wisely as possible.

The learning objectives of the lighting audit are many. Through engaging in the activities, participants will define terms associated with an energy audit. They will also identify the components to include in an outdoor energy/lighting audit and prepare and conduct their own outdoor energy/lighting audit. Participants will analyze data from the school/neighborhood outdoor energy/lighting audit, write recommendation/improvement options for more efficient lighting, and then calculate the savings realized by using more efficient lighting. Finally they will write out observations and measurements about current outdoor lighting and then develop and present an action plan to school or city officials about the results of the lighting audit, measurements, and options using PowerPoint, photos, worksheets, and designs.

4.4 Summary of the Activities

Activity 1 has vocabulary for students to become familiar with. There is a glossary, a fill in the blank quiz, and an answer key. Activity 2 is the Energy Lighting Audit. The audit could involve auditing part of a school campus. Or the audit could be an audit of the outdoor lights in students' neighborhoods (i.e. park, streets, school). The audit includes calculating energy consumption of the lights in the area.

Excerpt from Activity 2: Energy Lighting Audit

Your instructor will place you into groups of three or four. Each group picks a different building at your school to use in the lighting audit. Make sure the building has more than a half dozen lights on the exterior.

- Measure the dimensions of the building and sketch it to scale on a piece of graph paper. Be sure to write the length and width on the sketch.
- On your schematic of the building, draw the location of the lights and where you think the light will fall (e.g., on the ground). You can figure out where the light will fall by looking at the shielding (if any) and where the light is pointed.
- Take a picture of the fixture, close enough to identify it later.
- Identify the kind of shielding. Match it to one of the pictures in the package. Identify the shape of the lamp.
- Come back at night as a group and confirm where the light falls for each fixture. Describe whether the area being illuminated is too much or too little for the task. Describe if the light falls where needed or beyond where it is needed, or if it is blocked by vegetation or another structure. Also, describe if there are overly bright or dark patches that hinder your ability to see what is around you.
- Record the color of the lamp (i.e. yellow orange, greenish white, bluish white, etc.)
- For every light that you see, record the watts and lamp type by interviewing the facilities staff. Ask about whether the lights are on timers or on light sensors (dust to dawn) or motion sensors. If the lights are on timers, then ask the staff what the approximate hours of operation are.
- Determine the annual operating costs of the lights in your audit. (This is for all of the building lights on average.)

The purpose of Activity 3 is to have the participant become more aware of the design elements like fixtures in the audit and make observations and measurements about how effective they are in performing the function for which they were installed. Participants choose 2 different types of lamps or fixtures from the audit. For each of these lamps, they each complete at least 2 measurements or observations. For instance a participant can observe whether or not a light is fully shielded and can measure the "footprint" of a luminaire by noting its watts per area lit. Activity 3 provides more in-depth analysis of the energy audit and gives the student more information to make good recommendations.

Excerpt from Activity 3. Measurement of Audited Lights

Choose two different types of lamps/fixtures from the audit. For each lamp prepare at least 2 of the following measurements.

- Determine pole height
- Determine power density or watts per area lit
- Determine light output in lumens
- Determine illuminance levels in footcandles (illuminance meter required)
- Various observations about the luminaires i.e. how are they controlled, are they full cut-off, etc.

Example: in writing a description of the 2 types of luminaires, describe the type of mount (wall, pole, ceiling, other), the color of lamp (white, orange, green), its location and purpose (parking lot, walkway, intersection, park/green area, over a door), the task for which it is lighting (driving, walking, reading, facial recognition, security camera).

Activity 4 asks participants to produce a revised master plan. This could include the entire campus, part of the campus, their neighborhood, or one aspect of the neighborhood. Students (individuals or teams) present their revised lighting plan to the class and give explanations for changes or for keeping the status quo for all fixtures in a given area. Part of this revised lighting plan includes re-calculating the energy consumption of the lights as explained in Activity 2. Did the participants save money for his/her school? With adults in the community, students can possibly use the revised lighting scheme as part of a presentation to a planning and zoning meeting of their city government.

Excerpt from Activity 4: New Lighting Plan and Audit

Produce a revised lighting scheme for your school campus or neighborhood.

- Design a visual master plan for your campus:
- What are your goals for the plan?
- Show a diagram on graph paper of your new lighting plan.
- Take into account these areas (you are welcome to make your own assumptions, just be consistent) and address each area in your final presentation.
    - How will it be used? A lot, a little? Around a classroom building? In a ballpark or a walk/cycling path? Outside restrooms or in a parking lot? To illuminate a sculpture or fountain?
    - What are the hours of use?
    - What safety precautions are in place?
    - Has glare been reduced or eliminated?
    - What types of luminaires are you recommending and why?
    - What is around your park/campus? Residential, open space, businesses, mixed use?

Excerpt from Activity 4: Design New Lighting Plan and Audit, continued…

Using the material you have learned determine:

- If all the lights in the audit are now necessary. If not, why not?
- For what task/purpose is a lamp used? Is the current light adequate to perform this task? List reasons either way.
- Is there a money saving alternative? Give reasons why and why not.
-

Re-calculate the energy consumption of the lights for the revised plan using the equations from the audit in the second activity. Have you saved money? What is the pay off time of any new equipment that was recommended to be purchased (the difference of purchase cost and "energy savings" cost over time equals energy saved over time).

One of the successful uses of the School Outdoor Lighting Audit took place as an international educational videoconference on light pollution in which students from a middle school in Arizona reported their results from the audit to middle school students from Chile. The students calculated the cost and energy expended before and after changing to economical, energy-saving bulbs. Both groups of children enjoyed the cultural interchange and asking questions.

5. GLOBE AT NIGHT

5.1 Overview

The GLOBE at Night program[9] (www.globeatnight.org) teaches about the impact of excessive artificial lighting on local environments, and the ongoing loss of a dark night sky as a shared natural resource for much of the world's population. Because of population growth, increasing light use and, in some cases, poorly designed fixtures, 99 percent live in areas that are considered light polluted, according to the National Parks Service. With two-thirds of Americans not able to see the Milky Way from their backyards, one main goal of the GLOBE at Night program is to educate the general public that many of the solutions to light pollution issues center on proper illumination engineering. Illumination engineering is a way to provide practical and effective measures by which obtrusive aspects of outdoor light usage can be minimized, while preserving safety, security, and the nighttime use and enjoyment of property. These measures are intended to curtail the degradation of the nighttime visual environment, reduce light trespass, glare, energy use, and resource waste by encouraging lighting practices that direct appropriate amounts of light where and when it is needed, increasing the use of energy-efficient sources, and decreasing the use of poorly shielded or inappropriately directed lighting fixtures.

At the heart of the program people are invited to observe the prominent constellation Orion at least once over a two-week period each March and compare the number of stars that are visible using their unaided eyes with a series of on-line, downloadable charts that show how Orion would appear in skies ranging from very dark to very bright skies. An objective alternative to measure night-sky light pollution levels is to use the Sky Quality Meter (SQM), manufactured by Unihedron (www.unihedron.com). The SQM measures how much light strikes its sensor. The meter then converts that amount of light into units of magnitudes per square arc-second or a brightness per area. The larger the number read on the meter display, the darker the sky. A meter reading of 21.00 indicates a very dark site, while a reading of 16.00 indicates a light polluted sky. Typically in a medium-sized city, the faintest star you can see has a "limiting magnitude" of 3 or 4. These correspond to SQM measurements of 16.88 or 18.04 magnitudes per square arcsecond, respectively. Most people cannot see stars fainter than a limiting magnitude of 6, which corresponds to almost 21 magnitudes per square arcsecond.

GLOBE at Night has grown from a prototype project centered in Arizona and Chile to a global cornerstone program of the recently completed International Year of Astronomy 2009 (IYA2009). GLOBE at Night set a record in 2010 with more than 17,800 measurements of night sky light pollution from people in 86 countries, with nearly 11,000 coming from the United States. More information can be found at www.globeatnight.org.

Many of the participants in the 2010 campaign emerged eager to make changes in their lifestyle to use less energy and share these changes with their community. And since light pollution is something on which students can have a significant impact, teachers were really excited to have something that the kids can use at home, in their schools, and in their communities.

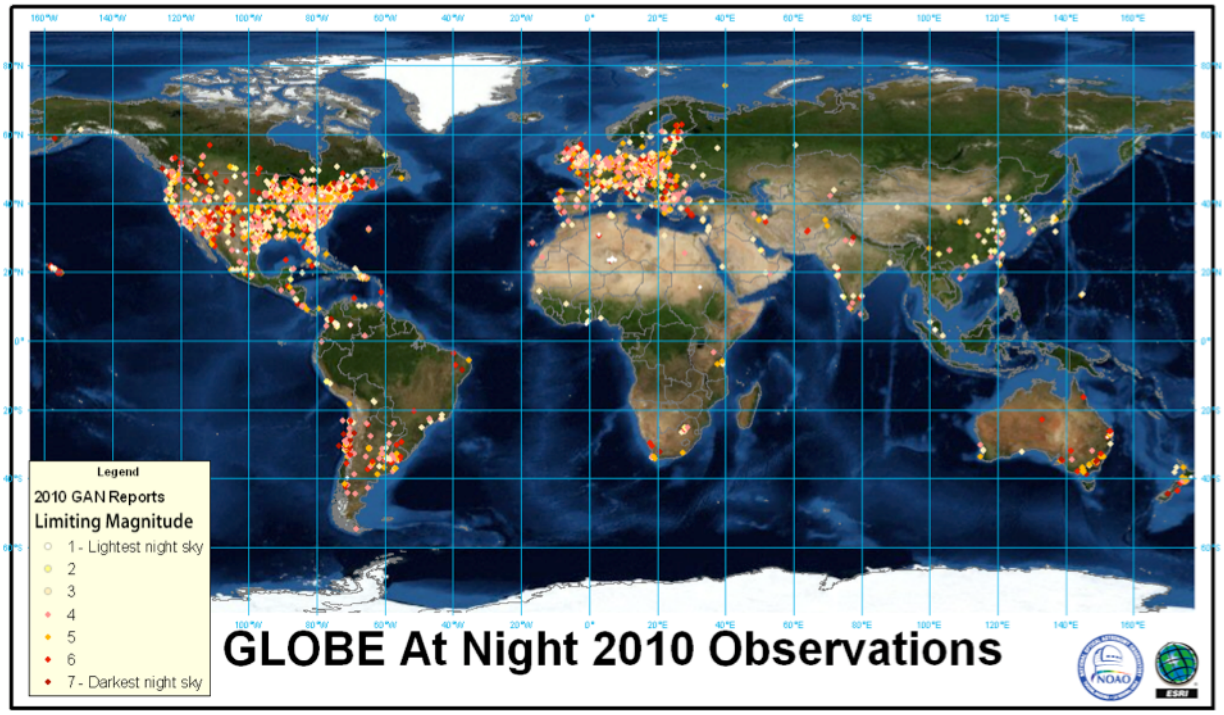

Figure 6. GLOBE at Night measurements in 2010: the brighter dots indicate brighter skies; the darker dots indicate darker skies. The range in limiting magnitudes is 1 (brighter) to 7 (darker).

5.2 Using the GLOBE at Night Database and the Sky Quality Meter

With over 50,000 data points from 5 annual campaigns, the GLOBE at Night data (downloadable in 6 formats) can be compared over time to look for changes and trends. The data can be compared to population density or with nighttime photography and spectroscopy of lights. The data can also be used in a lighting survey, to search for dark sky oases or to monitor ordinance compliance. Recently the data has been compared with telemetry of the Lesser Long-Nose Bat in Arizona to examine whether or not the bats are preferentially staying in darker areas while traveling between roosts and foraging areas.

The GLOBE at Night program and its database are resources to initiate energy-conserving changes for illumination engineering in communities. In one case, what started during GLOBE at Night 2009 with an Oklahoma mother and son taking measurements of environmentally friendly car dealerships and older dealerships (without “box” lighting) ended up as a team of high school students collecting digital SQM measurements and visual measurements of the night sky brightness. They took measurements at 476 different locations in their city, developed a night sky brightness map to determine the quality of lighting and presented their findings to the Environmental Control Advisory Board (ECAB). As of mid-2010, a group is working on a final draft to revise the lighting ordinances for their city and ultimately to retrofit city lights.

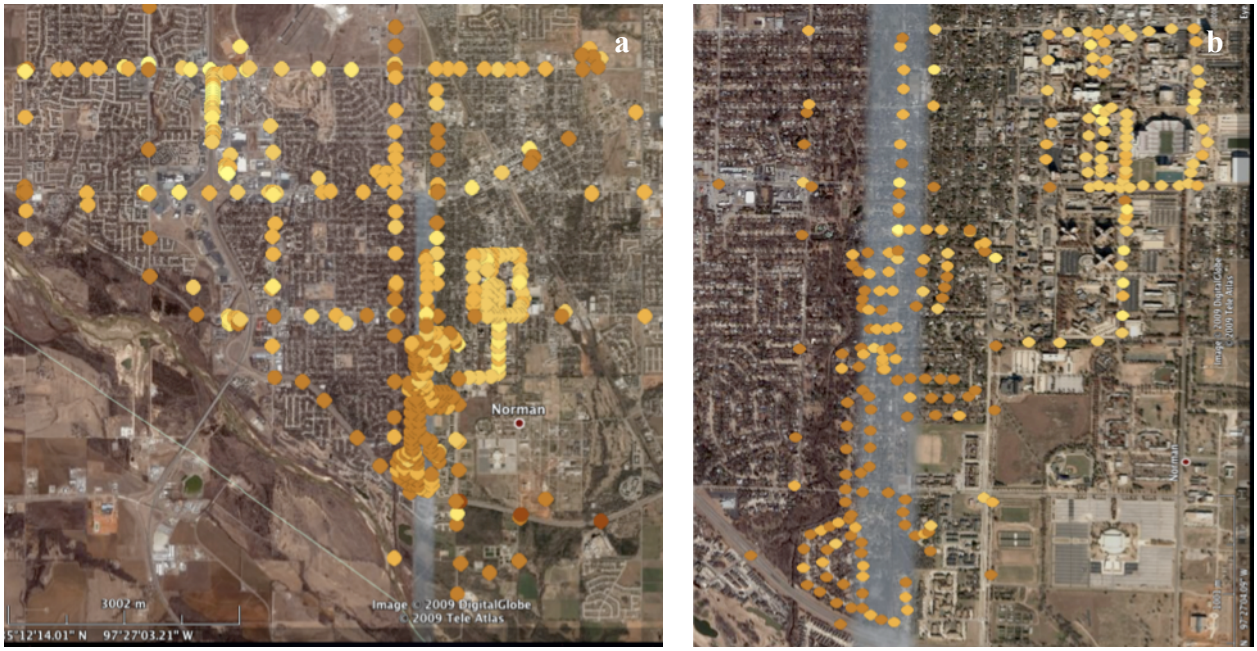

Figure 7. a) 476 GLOBE at Night measurements of a city; the brighter dots indicate brighter skies; the darker dots indicate darker skies. b) Zooming in to the densely sampled area in Figure 7a.

6. SUMMARY

With more and more of the world's population concentrated in urban centers the impact of light pollution in terms of both wasted energy, ineffectual use, and loss of the night sky has become ever more acute. NOAO and its collaborators have developed educational light pollution kits with hands-on activities, which raise public awareness of this issue and provide concrete examples of how it can be addressed. Over the past few years the kits have been in use (in whole or in part) by 1000's of individuals worldwide. As feedback is received from users and optical engineers, the kits will be updated to better serve the community.

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