Light Pollution around UGA's Observatory as Measured with an iPhone Spectrometer.

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The purpose of this experiment was to get a sense of the light pollution around UGA's Observatory (located on top of UGA's Department of Physics and Astronomy, Athens, GA). We design and calibrate a spectrometer made from an iPhone 5 to perform spectroscopy on seven outdoor light sources in the area of UGA's Physics building. Because the iPhone has a visual range camera, measurements were done in the visible range (390 - 700 nm[11]). Therefore, this experiment focuses upon that range which most affects visual range Astronomy. In this report, we present spectra of those seven outdoor light sources. From the analysis of these spectra, it is possible to make a objective claim as to the most polluted band of the night sky for astronomical measurement at UGA's observatory. We present the result that the green to red band (500 to 620 nm) is the most polluted band around UGA's observatory, with around 570 nm being the peak pollution band.

I. INTRODUCTION[1–8]

Light pollution has several qualitative definitions (Cf. e.g. Verheijen 1985[1], Cinzano 2000[2], Hollan 2008[3],Marin 2009[4]). Most generally, light pollution can be regarded as the alteration or degradation of natural light sources as a result of artificial or "man-made" light. Natural light sources, of course, are those that are not man made. During the day time, the most obvious natural light source is the sun. During the nighttime, natural light sources include the moon and the stars. The study of light pollution's effect on the environment has been vast and broad. It has been studied for its adverse effects on both ecosystems and health (Cf. e.g. Knez 2001[5], Bullough 2006[6],Perry 2008[7]) The fact that it is harmful is evident in its terminology.

Most prevalent to our studies, however, is the adverse effects which light pollution have upon astronomical measurement. Astronomy, in order to be both accurate and precise, must minimize both light pollution effects and atmospheric effects. Light pollution has the effect of washing out astronomical data. I.e. in visual band astronomy, astronomical detectors detect the high count light pollution effect rather than the low count science target signal. Atmospheric effects (not studied in this report) have the effect of manipulating incoming parallel wavefronts which produces images that are shifted on the detector. Of course, due to these effects, most research-level telescopes are built at high-altitudes in locations that are by and large free from light pollution (E.g. Keck observatory[9], Gran Telescopio Canarias[10]). The UGA observatory, used primarily for teaching purposes, however, is not.

The UGA observatory is built at a less than ideal location: in the center of UGA's campus, right by the famous Sanford Stadium, in a city that is densely populated and therefore prone to light pollution effects. We therefore determined that it might be useful to get an objective measurement as to the most polluted bands surrounding the observatory. Limited to the use of an iPhone 5, sky intensity measurements were ruled out (We performed intensity measurements at about every 3 miles from a radius of about 20 miles outside Athens. These measurements proved useless, and we were forced to conclude that the iPhone camera is not sensitive enough to perform such surveys.). Spectroscopic measurement of the common outdoor lighting sources (in the manner of e.g. Cinzano 2014[8], Hollan 2008[3], Lewis 1999[13], Maslowsky 2013[14] in the area was therefore determined to be the most viable means to achieve the goal of this experiment.

A spectrometer is a fairly simple instrument that detects and analyzes specific wavelengths of electromagnetic radiation.[12] It utilizes a diffraction grating to disperse a light beam into its wavelength pieces. Because artificial light takes advantage of electrons in certain elements jumping between certain energy levels, which thereby produces a photon of a specific wavelength, it is possible to determine atomic composition through spectral analysis. Our spectral analysis, which measures normalized intensity as a function of wavelength, allows us to determine the most polluted wavelengths of the sky around UGA's observatory.

II. METHODS

A. Instrument Design

The spectrometer utilized in this experiment was built based on a design for a smartphone spectrometer found on CheminTen, a science-based Youtube channel.[15] As such, the principle components of the spectroscope consisted of a smartphone, a diffraction grating (1000 lines/mm), and a long, diagonally oriented tube used for aiming of the device and limiting of light incident on the measuring apparatus. In the construction of such device here, an iPhone 5 was used for the smartphone, and the aforementioned tube consisted of a cardboard tube lined

with carbon paper – this was so as to limit reflection in the tube. Black duct tape was used to maintain the integreity of the tube, and black electrical tape was used for anchoring of the carbon paper, as well as attachment of the diffraction grating and tube to the iPhone and the creation of the slit on the end of the tube (used for further limiting of light intensity). The slit and diffraction grating were both oriented so as to create a lengthwise spectrum in iPhone pictures, with shorter wavelengths on the left side of the pictures.

B. Calibration

With our spectrometer having been built, steps were taken to ensure that our spectra appeared in approximately the same location on each of our images. The iPhone spectrometer must be held in a specific manner for this to be achieved. This is one limitation of our portable instrument, and while steps were taken to minimize this effect, it was not possible to completely get rid of slight spectra offset. In any case, it is accounted for in our error estimation.

Calibration of a spectrometer requires two known wavelengths. The goal of calibration is to get wavelength values instead of pixel numbers on the x-axis of your one-dimensional spectral plot. We utilized two light sources to do this: (A) a HeNe laser ($\lambda_1 = 632.8$ nm) and (B) a sodium lamp ($\lambda_2 = 589.3$ nm, because our spectrometer was not sensitive enough to detect the doublet, we used the mean of the two wavelengths.[16]). Spectra were taken of each of our calibration sources, about 10 for each source. Each of these spectra were analyzed in our spectral analysis routine (written in *Python*). To obtain a one-dimension plot of intensity vs. pixel location, pixel values along the vertical image axis were summed, and plotted as a function of the horizontal pixel location.

These plots were examined for each source, and those plots with the least noise were utilized for our spectrometer calibration. The remaining plots were used for error estimation. Calibration, after obtaining a one-dimensional spectrum, is very straight forward. By plotting both spectra (HeNe and Sodium-Vapor) on the same plot, we can find the pixel value difference (ΔPix) between the two intensity peaks. Because we know $\Delta\lambda = 632.8 - 589.3 = 43.5$ nm, we know that the pixel location difference between our two peaks on our spectra correspond to 43.5 nm. We can thus find the nm per pixel (K). I.e.

$$K = \frac{nm}{pixel} = \frac{\Delta\lambda}{\Delta Pix}$$

With this information, we were able to simply assign wavelength values to the x-axis and use the same wavelength values through the rest of the experiment.

Error estimation for our spectrometer was done by plotting the other calibration images obtained according to the wavelength coordinates obtained by the above procedure. By observing the peaks of these other images, we were able to get a wavelength error range for our spectrometer (σ_λ).

C. Data Collection

Upon calibration being performed, several varieties of artificial light sources nearby to the UGA Observatory were identified, and were subsequently measured spectrally utilizing the constructed iPhone spectrometer. These sources were chosen so as to give a variety of colors and sources. The identified light sources consisted of yellow and white (The white lights are also called Sanford Bridge lights in this survey) streetlights, yellow and white lights with spherical covers (these are a distinct and common feature on the UGA campus), yellow parking lot lights, white sidewalk lights, and the composite spectra of the Sanford Stadium lighting. Each source was measured with care given to limit overexposure of any camera pixels, which would negatively effect analysis efforts.

In order to get some concept of relatively how much of a factor each of the chosen light sources were in the overall light pollution spectra for the observatory, all light sources of these types within 500 feet of the UGA observatory were documented. The proportion of each type of light was to be used in creating a composite spectra in the Spectral Analysis portion of the experiment. While 500 feet is an arbitrary radius of measurement, it is beyond the scope of this experiment to assess the light composition of the whole of Athens, or even the UGA campus. As such, this area was chosen with its proximity to the location in question in mind, as well as its containing each of the six types of lights in question. Given the composite nature of Sanford Stadium's spectra, as well as its extreme power relative to the other light sources, it was not included in this proportionality measure.

D. Spectral Analysis

With calibration performed on our spectrometer, spectral analysis was very straight forward. Using the wavelength coordinates found in calibration for the dispersion axis, we created one dimensional plots for each of the light sources observed. One dimensional plots for outdoor light sources were created in the same way as our calibration plots. Again, the least noisy spectra were utilized as a representative spectrum for each respective source. Spectra were normalized according to theirselves so that the maximum intensity is 1.0 for each spectra.

In addition, the numbers of different light types within 500 feet of the UGA observatory were converted to proportionality measures. In doing so, these numbers were divided by the max frequency and then multiplied by there respective spectra to get a composite spectrum: one that gives an idea of which light source (and which wavelength range) most pollutes the UGA observatory.

III. RESULTS & DISCUSSION

A note about the spectra which we are about to present: Because we did not preprocess our spectra (i.e. by accounting for bias, dark-current, and flat-fielding), our data is (1) noisy, and (2) not a true emission spectrum. A true emission spectrum would have zero intensity everywhere but the emitted lines (i.e. the equilibrium would be at zero). However, because our spectra were not preprocessed, our equilibrium's are non-zero. However because the goal of this experiment is to determine the most polluted visible wavelength region near the UGA Observatory and not to measure intensity of our light sources (such a comparison would not be warranted even if we did preprocess our images, there are too many uncontrollable variables to consider such as distance, angle of the spectrometer, etc.), this is not so much an issue.

In addition, spectra will be presented as a one-dimensional plot, with the source image (not necessarily to scale) displayed underneath.

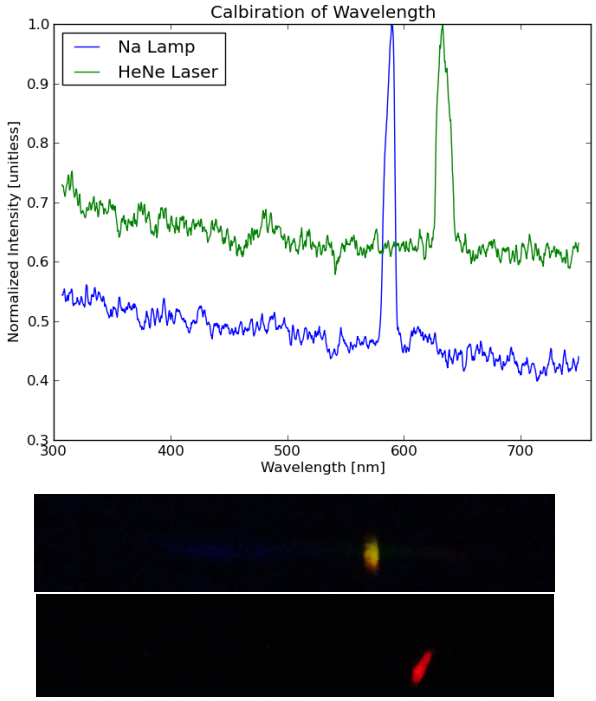

FIG. 1: Calibration of our instrument using a HeNe laser and a sodium lamp. The HeNe laser spectrum is plotted in green, whereas the sodium lamp spectrum is plotted in blue. This plot gives a very clear idea of the types of noise experienced. The equilibrium for HeNe is around 0.65, whereas that of Na is around 0.5. As discussed earlier this is due to the lack of preprocessing.

A. Calibration

We obtained a calibration value:

$$K = 0.369\ nm/pix$$

No error is reported for this value because our error measurements were done not for K but for our wavelength measurements. After applying this value of K to our pixel locations and performing the error estimation routine described in our Methods section we obtain the following:

$$\sigma_\lambda = \pm 3.0\ nm$$

This means that any given point in our presented spectra falls in a range of ±3.0 nm. This value is to be expected given the design of our spectrometer. If our spectrometer was stationary, we would expect this value to be very close to zero. However, because the spectrometer was built to be portable, and that portability affects measurement (i.e. in terms of measurement angle, distance from the spectrometer slit, etc.) our reported error is reasonable.

Calibration of our spectrometer yielded the following plot.

B. Individual Spectra

This section is very plot heavy, with seven outdoor light sources examined and their plots displayed. The lights are given names according to their appearance and also their location. The type of light is discussed, but not the point of analysis since the goal of the project is to find the most polluted visual wavelength band of sky around UGA's observatory.

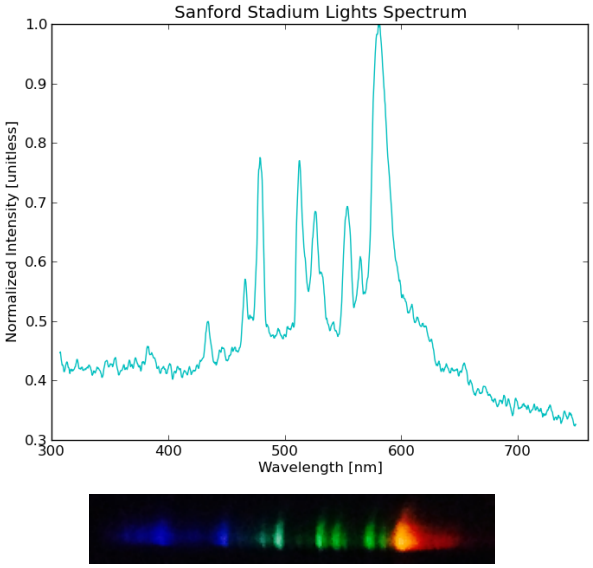

FIG. 2: Sanford Stadium lights proved a difficult consideration in our experiment. Given that they are so intensely bright, and given their proximity to UGA's observatory, it is likely that they must be off for any astronomical measurement. Due also to their inability to be counted, they were not included in our composite spectrum below. The spectrum however is very interesting, with several peaks in the blue, green, and one strong peak in the orange (likely sodium again).

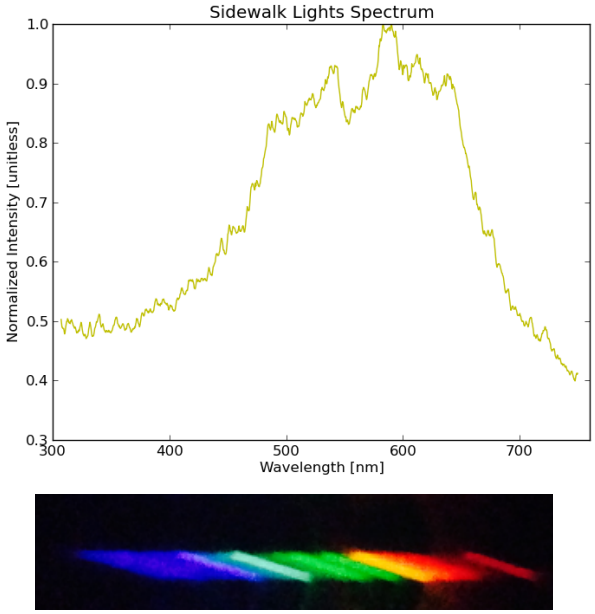

FIG. 3: By far the largest pollutants of our study, these small lights light the sidewalks by the UGA Physics building. They were not included in our composite spectrum below because they face the ground only are only at a height of a couple feet. Any light pollution these light sources would be as a result of reflection, which is likely undetectable with the experiment's instrumentation. Based on the continuum these lights are either incandescent or halogen bulbs.[14]

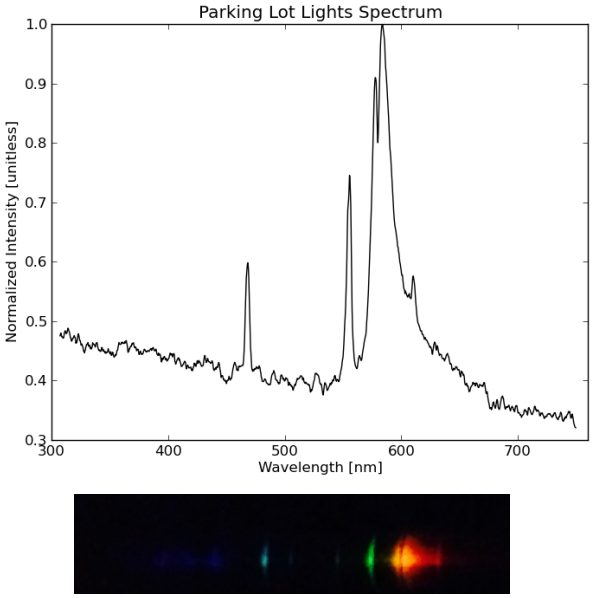

FIG. 4: Spectrum of various suspended yellow lights used for illumination of parking lots near the Physics building. We get a small peak in the blue range (460 nm), a peak in the green range (550 nm), and a very strong sharp peak in the orange range (590 nm) that seems to suggest sodium emission. This light is likely high-pressure sodium, based off the peaks of sodium and that green band emission.[13]

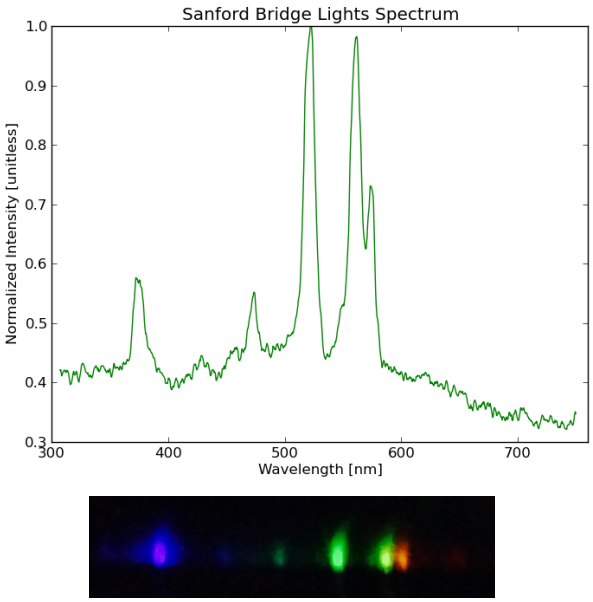

FIG. 5: Spectrum of white streetlights that light up Sanford Bridge near Sanford Stadium. We get a medium-sized peak in the violet range (370 nm), a small peak in the blue (480nm) and two very large green peaks (at 520 & 550 nm). This spectrum suggests a wider pollution range than those of the parking lot lights, however we will see that these lights are not all that frequent in our composite spectrum.

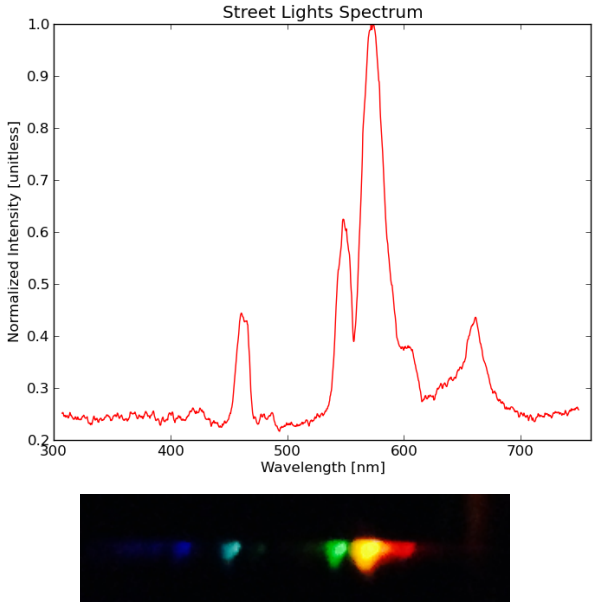

FIG. 6: Spectrum of street lights that light up Sanford Drive near the Physics building. We get peaks in the blue (450 nm) green (550 nm), and orange (570 nm). The peak around 650 nm is a result of noise. The strong orange peak is likely mercury. The spectrum suggests that the light source is mercury vapor.[17]

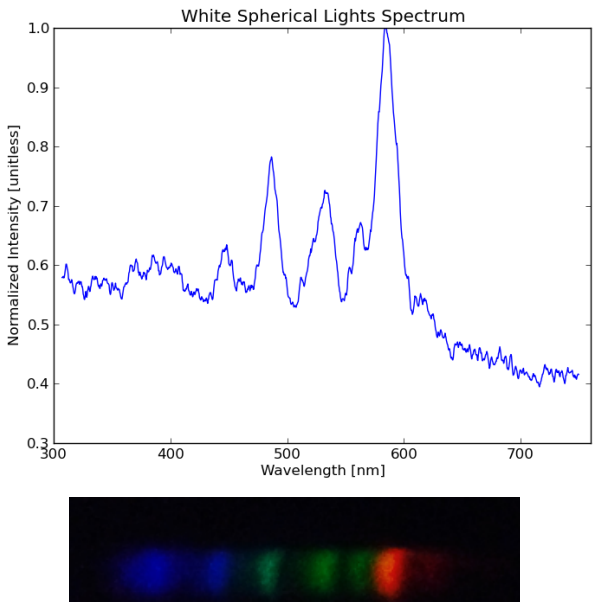

FIG. 7: White spherical lights, so called because of their appearance, seem to have a fairly wide spectrum. With many peaks, as well as blue emission, the highest peak is likely sodium (590 nm).

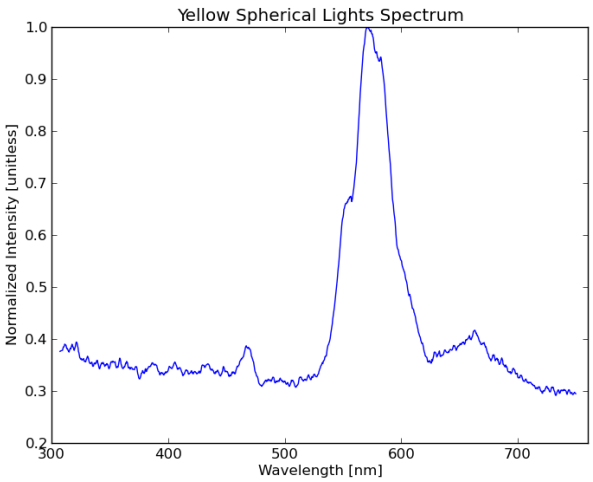

FIG. 8: Based on our results, because of the high frequency of these lights in the area surrounding the UGA Physics building, the largest contributor to light pollution around the UGA observatory. This light seems to pollute a band extending from the green to the red (540 nm to 620 nm) with a peak around 570 nm. Identification of such a light source is very difficult and any attempt to do so would be nothing more than speculation.

C. Composite Spectrum

Through the estimative proportionality observations for each of the six light types, the following numbers for each of the light types were found: 30 Yellow Streetlights, 31 Yellow Spherical Lights, 5 White Spherical Lights, 35 Sidewalk Lights, 2 White (Sanford Bridge) Streetlights, and 13 Parking Lot Lights. These numbers were taken into consideration, and utilized as weights on each of the individual light spectra, so as to attempt to provide a composite spectra for the UGA observatory. As has been noted, despite their large plurality in the studied area, the Sidewalk lights were excluded from the following composite graphs. This is because, while the lights likely do indeed contribute to the overall light pollution of the area, these lights point downwards primarily, and as such their contributions would be primarily reflections, and also would likely be undetectable with out measuring equipment on an individual source scale. As such, it was felt that they could not be adequately assessed with regard to their effect on light pollution.

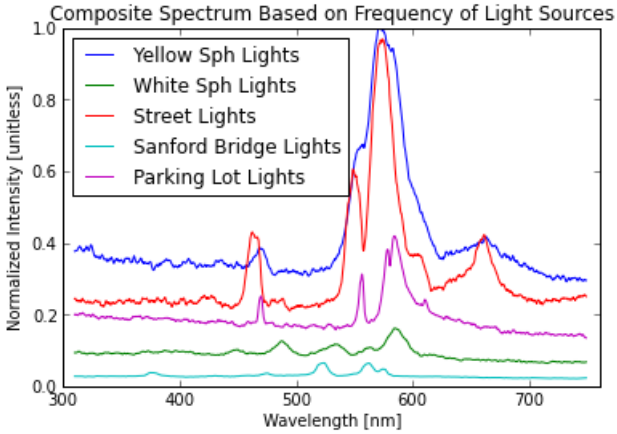

FIG. 9: Each spectra is individually scaled based on their frequency within the sampling area. As noted, yellow streetlights and yellow spherical lights were by far the largest contributors. However, regardless of the light source, the most prominent peaks tend to be concentrated in the region from 500 to 620 nm, with a clear peak around 570 nm for all light sources shown. There is also a common region of smaller peaks in the blues, around 450 to 490 nm.

By adding the above spectra to form one master spectrum and renormalizing, we obtained the following spectrum.

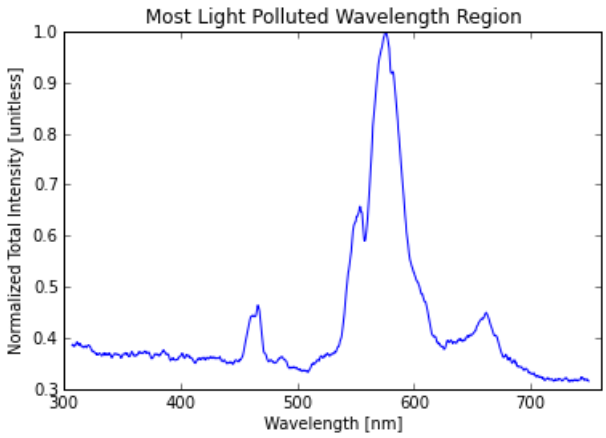

FIG. 10: Added and renormalized spectrum utilizing the five spectra displayed in figure 10. This plot reconfirms our above analysis. The most polluted wavelength range is from 500 nm to 620 nm, i.e. the green to red visual wavelength bands. There is a small peak around 470 nm that is not very significant compared to the very polluted green/red band. The peak around 660 nm is noise, a result of reflection inside the instrument tube.

IV. CONCLUSIONS

Based on analysis of the spectras of the aforementioned seven light sources around campus (two of which were excluded from the composite), a light pollution signature

with a primary band from 500 ±3 nm to 620 ± 3 nm, with a peak value at 570 ±3 nm, as well as a smaller peak at around 470 ±3 nm. This data is in accordance with the frequency of the aforementioned light sources in the region immediately surrounding the UGA Observatory. Sanford Stadium, as a major source of possible light pollution on campus (though the lights may be off during measurements), has several peaks, with the strongest at 590 ± 3 nm and several other strong peaks at 480 ±3 nm, 510±3 nm, and 560 ±3 nm. Sidewalk lights are not upward-facing, and thus are likely somewhat altered in their effects on light pollution, but given their plurality may still be significant. In this case, they would have a large range of affected light, ranging from 490 ±3 nm to 630 ±3 nm in wavelength.

While the near-universal agreement of the studied light sources on these wavelengths would suggest that this spectra, at least at the extremes, is accurate, nevertheless there are some methodological concerns with it. Principal among these is the lack of a measure of intensity from each light source. As previously noted, part of this lack is due to issues involving obtaining a standardized measure of light output, given that these light sources output light in a variety of directional signatures, and that the positioning of these various lights can make it difficult to obtain standardized distance readings. However, intensity readings were taken nevertheless. While these readings agreed with Malus' Law in a calibration test, in terms of practical usage these intensity readings (done with an iPhone 3) proved impractical both in measuring overall sky brightness and in measuring individual light sources effectively. Overall sky brightness was too small to be adequately detected using this device – meanwhile, aiming the device proved difficult in non-laboratory settings, and readings were generally quite inconsistent. Given this, further research in this field should be approached with an intensity or light output meter of greater sensitivity and consistency than a smartphone as a supplement. Hopefully the potential identifications of the types of light sources used in this region of campus may also allow for intensity readings to be taken in controlled laboratory conditions, as opposed to the field.

Another concern of note was that only light sources located nearby to the UGA Observatory were analyzed, and that relative proportions for each variety of light were also only based on the Observatory's immediate surroundings. Of course, Athens, GA, as well as UGA both have light pollution spectras that are more complicated beyond this sample. However, given the arbitrary nature of any area of sampling, as well as the possibility of different light makeup of different regions of the town, it was concluded that to get a more accurate idea of the overall light pollution at the UGA Observatory, a great census of varieties and frequencies of light throught the town and campus would be necessary. This is obviously beyond the scope of this experiment, and as such further research on this topic should consider reasonable methods of characterizing light pollution more effectively as an approximation. Alternatively, GIS technology may be well-applied to this sort of census. Such a research method would also allow for accounting of altitude and environment factors, which are also weaknesses of this study.

A third concern, which has already been partially noted, is that no preprocessing or alterations after the taing of the spectras was performed. This likely had some effect of causing less clear than desired spectral lines, and may have also contributed to some of the blurring that appears present in the sidewalk light spectra (likely as a result of slanting in the original spectrum). However, the in-field measuring of the spectra, which obviously then would cause somewhat different environmental conditions for each spectrum, is likely also a cause of the noise present in the spectra. Preprocessing may have helped with these effects, but considering the relatively clear peaks found regardless (as well as the exclusion from the composite of the sidewalk light spectra, the only one demonstrating any slanting issues), then the benefits of such processing may not greatly effect the results of the analysis.

Overall, this experiment did accomplish its goal of finding a definitive range of light wavelengths which would be particularly impacted by light pollution. Given the quite common nature of many of the light sources identified (often sodium, incandescent, or halogen were the most likely sources for the spectras identified), as well as the general agreeance in terms of strongest peak with the Sanford Stadium lighting, this spectra is likely a moderately accurate depiction of the light pollution throughout campus, and possibly even Athens, even if (as noted) future research would be needed to adequately confirm such a result. This research can be utilized to make more informed judgments and corrections for noise in any visible light measurements taken at the UGA Observatory, especially if the Sanford Stadium lights are on.

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