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A Skyglow Evaluation of Citywide LED Streetlight Retrofit in Flagstaff (AZ), Phoenix (AZ), and Los Angeles (CA)

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Abstract

Light Emitting Diodes (LEDs) are known for their high energy efficiency and low maintenance cost, which, according to researchers, are paid by the world's disappearing dark sky. Many cities in the US have conducted citywide LED streetlight retrofit projects, whose effect on skyglow, however, has rarely been quantified. This exploratory study investigates the skyglow and light pollution changes over time for three US cities that adopted different retrofit strategies: Flagstaff, Phoenix, and Los Angeles. The data from both the satellite VIIRS and citizen science projects indicate stable light radiance and sky brightness trends in Flagstaff, which adopted Phosphor-Converted Amber (PCA) and Narrow-Band Amber (NBA) LEDs to preserve its dark sky heritage. Phoenix experienced a better sky quality with 2,700 Kelvin LED bulbs. In Los Angeles, where 4,000 Kelvin LEDs were used, the sky got brighter.

Introduction

In the 1970s, High-Pressure Sodium (HPS) and Low-Pressure Sodium (LPS) bulbs were the most popular source of street lighting in the US. During the mid-2000s, many US cities launched the Light Emitting Diodes (LED) streetlight retrofit projects primarily to enhance energy efficiency and reduce streetlight maintenance costs.[1] In 2006, City of Ann Arbor (MI) initiated the LED streetlight testing

[1] An Investigation of LED Street Lighting's Impact on Sky Glow (2017)

program;[2] in 2009, Los Angeles (CA) followed suit and even extended the program to citywide LED streetlight conversion.[3]

However, concerns have been raised because LED products, with a broader spectrum and shorter wavelengths than HPS and LPS bulbs, alter the spectrum of the artificial light. Research shows that LED streetlamps with a color temperature of 4,000 Kelvin, though largely reduce lighting cost and energy consumption, could increase light pollution by a factor of 2.5.[4] Also, the illumination of white-color LEDs has pervasive effects on the biological patterns of wildlife and the immigration behaviors of birds.[5,6] Moreover, inappropriate LED lighting can affect human vision and pose safety challenges for drivers and pedestrians at night.[7]

Reducing the pervasive effect of LEDs has long been a focus of researchers. The International Dark-sky Association (IDA) published recommendations on the design of LED streetlight to help preserve the dark sky. The suggestion is summarized as (1) adopt "warm-white" or filtered LEDs with Correlated Color Temperature (CCT) lower than 3,000 Kelvin and Scotopic Photopic (S/P) Ratio smaller than 1.2. A lower CCT value indicates a warmer color, and a smaller S/P Ratio indicates less excessive lighting; (2) adopt fully shielded fixtures; (3) use adaptive controls and avoid over-lighting.[8]

Flagstaff, Arizona, exemplifies this dark-sky-friendly LED retrofit strategy. In 2001, Flagstaff was given the first International Dark Sky City award from the International Dark-sky Association. Astronomers at the local Lowell Observatory and residents are proud of their long-standing dark sky. The city government of

[2] City of Ann Arbor Environmental News (2008)
[3] Office of the Mayor, City of Los Angeles (2009)
[4] The new world atlas of artificial night sky brightness (2016)
[5] Light at night disrupts nocturnal rest and elevates glucocorticoids at cool color temperatures (2018)
[6] Effect of anthropogenic light on bird movement, habitat selection, and distribution (2019)
[7] International Dark-sky Association (Accessed 2020)
[8] International Dark-sky Association (Accessed 2020)

Flagstaff had been strictly following the outdoor lighting ordinance enacted in 1958, using primary the LPS and HPS bulbs with CCT of around 2,000 Kelvin.[9]

However, a few years ago, Flagstaff had to prepare for a citywide LED streetlight conversion because the old, warm streetlamps were not be supplied after 2019.[10] Unlike many US cities that initiated the LED retrofit primarily for the cost reduction, Flagstaff launched the project with extensive research on reducing the detrimental, yet avoidable effect, of LEDs.

The Street Light for Enhancing Dark Sky (SLED) project in Flagstaff started in 2012. After years of research, consulting, and testing, Flagstaff eventually settled into two alternatives. The first one is known as Phosphor-Converted Amber (PCA), which shifts all the blue lights into yellow and results in a lighting condition quite similar to that created by HPS. The second option is the Narrow-Band Amber (NBA) LED, a special LED emitting only warm-color lights. With all the endeavors devoted to dark-sky preservation, Flagstaff was again featured by the IDA for successfully implementing the streetlight conversion program without increasing the city's skyglow.[11]

Enlightened by the LED design recommendations formulated by IDA and the fact that many US cities have accomplished the citywide LED retrofit, this study intends to conduct a light pollution exploratory investigation on three US cities before/during and after the streetlight retrofit.

Methodology

Overall, both qualitative and quantitative methods are adopted in this study. Specifically, the investigation primarily focuses on: (1) different LED lamp standards set by the city government; (2) change of the satellite Visible Infrared

[9] The City of Flagstaff Official Site (Accessed 2020)
[10] The City of Flagstaff Official Site (Accessed 2020)
[11] How Flagstaff, Arizona, switched to LEDs without giving astronomers a headache (2019)

Imaging Radiometer Suite (VIIRS) data; (3) change of the average sky limiting magnitude over time.

Cities are selected based on several rules: (1) have similar scales of the LED conversion and the scale is measure by both the quantity and percentage of LED replacement; (2) have completed the city-wide conversion by 2019 to to ensure the availability of post-conversion data; (3) have different LED conversion design and the distinction can be characterized by color temperature, bulb filters, and shielding feature.

City	Area (mi^2)[12]	Conversion Timeline	Conversion Scale	Bulb Feature	Shielding Feature
Flagstaff[13,14]	66	2018	Citywide	PCA/NBA	Some Shielded
Phoenix[15]	517	2017-2019	Citywide 100,000 +	2,700 Kelvin	Some Shielded
Los Angeles[16]	503	2009-2016	Citywide 190,000 + [88%]	4,000 Kelvin	Mostly Unshielded

Figure [1] City Characteristic and Project Design Comparison Summary For Selected Cities

By considering the above criterion, Flagstaff (Arizona), Phoenix (Arizona), and Los Angeles (California) are selected. As discussed, Flagstaff exemplifies a benchmark city with ideal LED streetlight retrofit strategies. Phoenix and Los Angeles, though with similar size and LED conversion scale, adopted different LED standards. Phoenix used 2,700 Kelvin bulbs with a warmer color than the 4,000 Kelvin one in Los Angeles.

After city selection, two measurements, namely, light pollution and sky limiting magnitude, are adopted to evaluate the skyglow change before/during and after LED retrofit. Specifically, light pollution is quantified by the satellite Visible Infrared Imaging Radiometer Suite (VIIRS) data as shown in Figure [2]. VIIRS measures the reflected radiance of the Earth into the sky and is available for years

[12] Wikipedia – US Cities (Accessed 2020)
[13] How Flagstaff, Arizona, switched to LEDs without giving astronomers a headache (2019)
[14] The City of Flagstaff Official Site – SLED Timeline (Accessed 2020)
[15] Street Transportation LED Program – City of Phoenix (Accessed 2020)
[16] LED – Bureau of Street Lighting Los Angeles (Accessed 2020)

from 2012 to 2019.[17] Even though VIIRS provides the corrected reflectance data, it is biased for direct annual comparison because variations such as clouding condition, image quality, and the sensor's sensitivity to blue light, can override the radiance change itself [See *Discussion*]. In this study, the VIIRS maps for years before/during and after the LED conversion are sampled for all three cities. The comparison is conducted for each pixel in the VIIRS image through scatter plots.

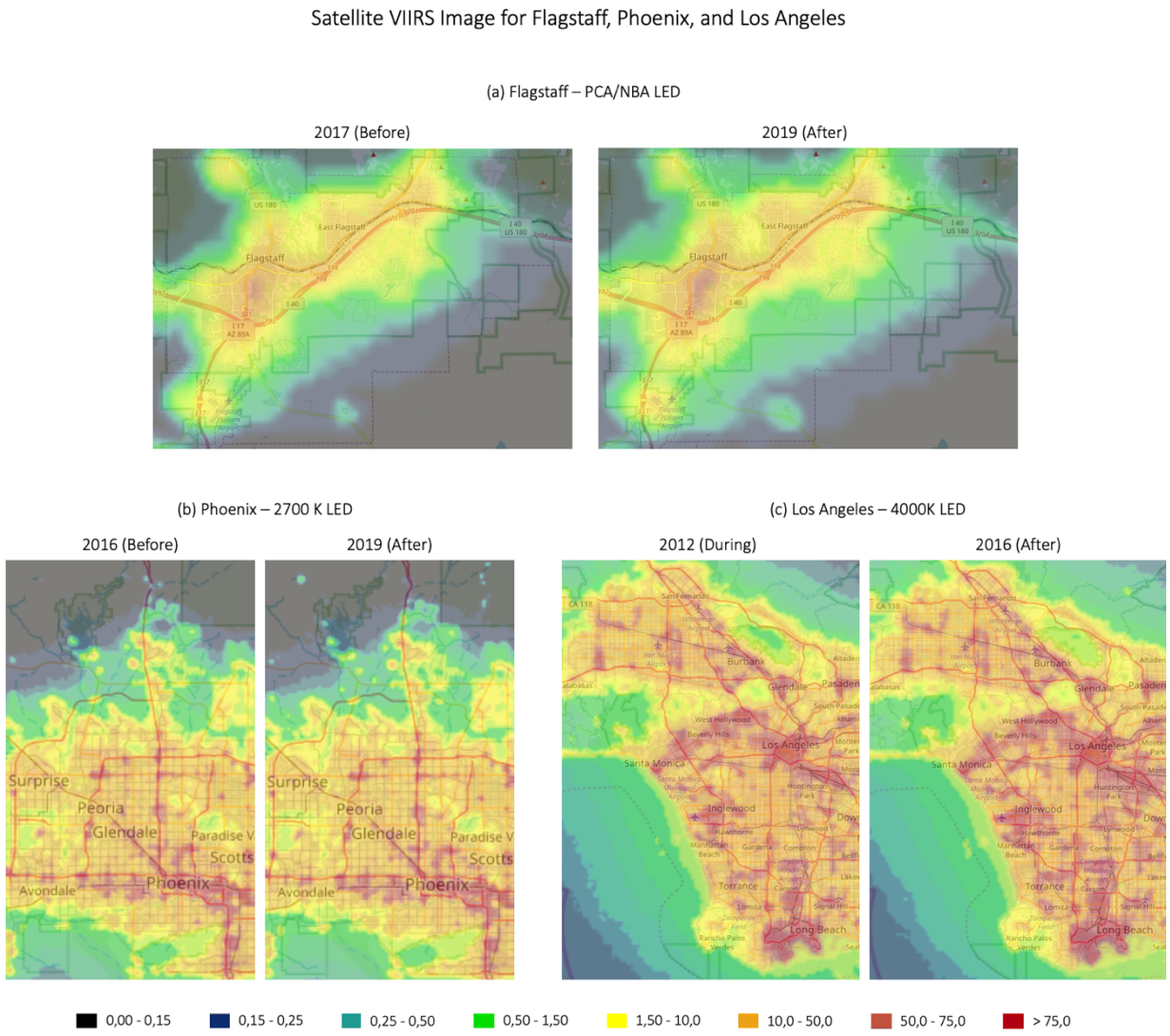

Figure [2] VIIRS Data (Raw) for Flagstaff, Phoenix, and Los Angeles ($10^{-9}\ W/cm^2\ *\ sr$)

[17] Earth Observation Group, NOAA National Geophysical Data Center (Accessed 2020)

Additionally, the sky limiting magnitude data collected from citizen science projects are used to characterize the sky brightness over time. The data are obtained from multiple sources: (1) Globe At Night (GaN)[18]: a citizen science project conducted annually to estimate the sky limiting magnitude observed by naked eyes; (2) Loss Of the Night (LON)[19]: an app used to estimate the limiting magnitude observed by naked eyes; (3) Sky Quality Meter with Lens (SQM-L)[20]: a single-channel broadband tool to measure the reflected radiance; (4) Dark Sky Meter (DSM)[21]: a tool to measure the spatially-averaged, multi-channel illuminance. Only observations under the "clear" cloud condition are used.

Result

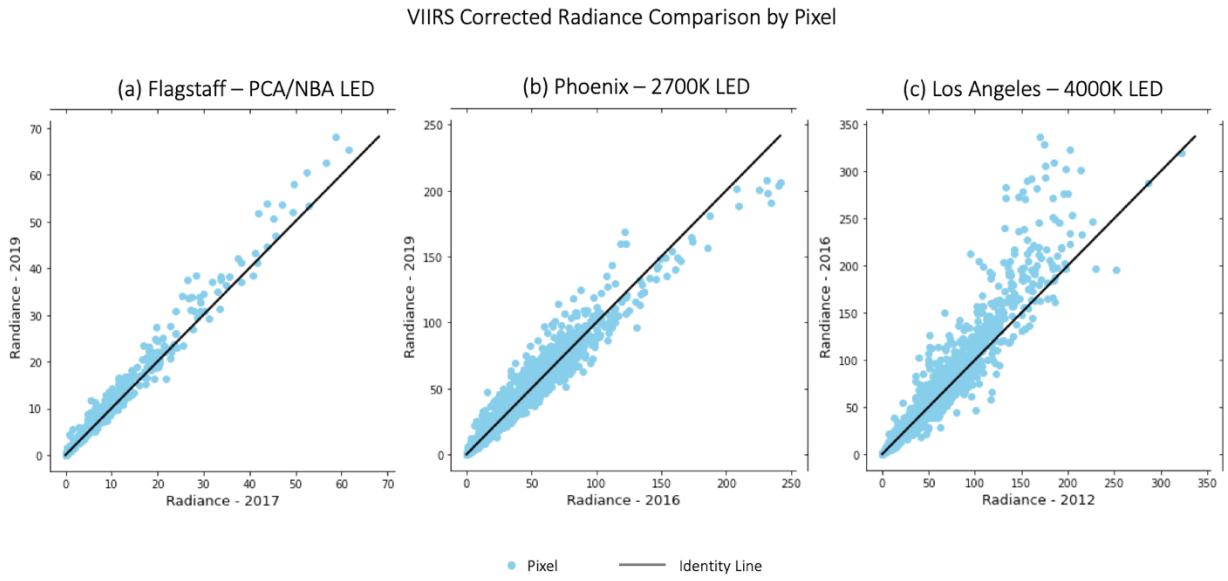

Figure [3] VIIRS Comparison by Pixel for Flagstaff, Phoenix, and Los Angeles ($10^{-9}\ W/cm^2\ *\ sr$)

For Flagstaff and Phoenix, the scatter plots in Figure [3] show the change of radiance for each pixel in the VIIRS imagery data before and after the LED

[18] Globe at Night Website (Accessed 2020)
[19] Science Learning Hub – Loss Of the Night (Accessed 2020)
[20] Sky Quality Meter Website (Accessed 2020)
[21] Dark Sky Meter Website (Accessed 2020)

streetlight conversion. For Los Angeles, the data in 2012 are used for analysis as the VIIRS image before conversion is unavailable. The scatter plot of Los Angeles shows the pixel radiance change from 2012, when the project was under implementation, to 2019, when the project was completed.

Overall, the range of axis value in Figure [3] shows the different levels of light pollution in three cities. From Figure [3a] to [3c], the level of light pollution increases. The result features the dark-sky heritage of Flagstaff and the severe light pollution issue in Los Angeles.

For the pixel radiance change before and after LED retrofit, Flagstaff, the city adopting PCA and NBA strategy, didn't see a huge increase of pixel radiance given that the points are randomly, closely scattered around the identity line. In Phoenix, the change was more observable as the points in Figure [3b] forms a broader band. Also, pixels with high radiance in Flagstaff slightly increased while those for Phoenix decreased. There is no evidence, though, to attribute the change of high-value pixels to the LED conversion. The situation in Los Angeles, however, was markedly different. The city that replaced the old HPS/LPS street lamps with 4,000 Kelvin LED saw a drastic increase of radiance value for the majority of pixels from 2012 to 2016, as most of the points stay above the identity line.

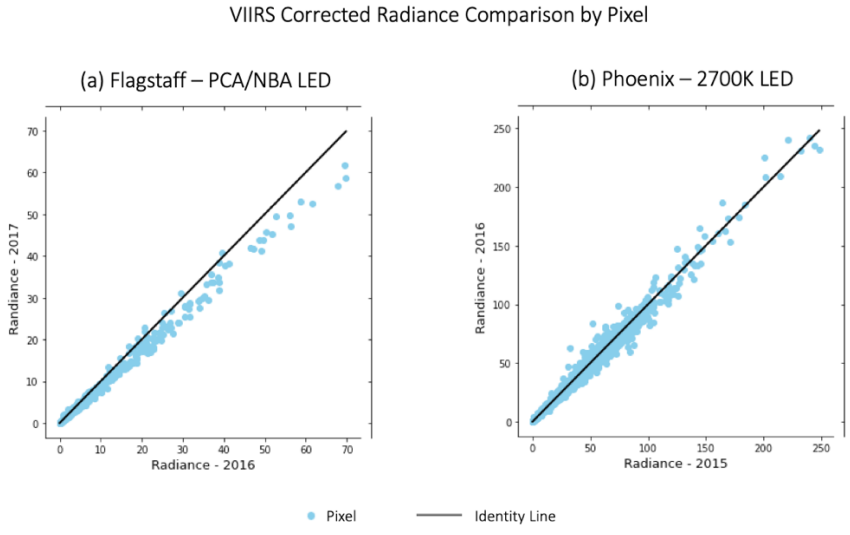

Figure [4] VIIRS Comparison by Pixel for Flagstaff and Phoenix ($10^{-9}\ W/cm^2\ *\ sr$) before LED Conversion

Overall, Figure [5] shows the change of average sky limiting magnitude in Flagstaff, Phoenix, and Los Angeles. The observations from GaN, LON, SQM, and DSM were first combined; then the mean and the 95% interval were calculated for each city in each year. Since a higher value of limiting magnitude indicates a darker sky, Figure [5] shows that Flagstaff had the darkest night sky among the three cities, a result consistent with that of Figure [3].

For Flagstaff, there is no obvious increase or decrease over time as the annual mean values fluctuated between 4 and 5. The 95% error bar is wide because there are not many observations in before 2020. The result is consistent with many conclusions in the literature that Flagstaff performed well in preserving its dark sky.

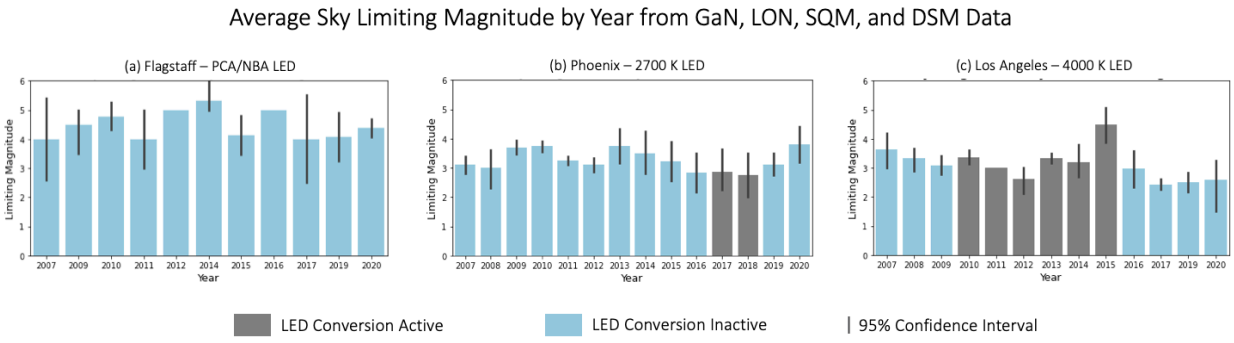

Figure [5] Average Sky Limiting Magnitude by Year

For Phoenix, there is a decreasing trend from 2013 to 2018 and an increasing trend ever after. The turning point coincides with the LED conversion project in the years 2017 and 2018. As there are more observations in Phoenix than in Flagstaff, the result shows a narrower bar associated with higher confidence about the mean statistics. Although the result is not sufficient to support the positive effect of LED conversion in Phoenix, it can still show that Phoenix is experiencing a darker sky after 2018.

Figure [5c] presents the change in Los Angeles. There is a general decreasing trend from 2007 to 2020, with a spike, however, in 2015. The chart is not sufficient to tell the reason behind that spike.

Discussion

The most critical limitation of this study is inherited in the data source. First of all, it would be problematic to derive any conclusive result by making direct annual comparisons of the radiance value from the raw VIIRS data. The VIIRS data is composed monthly with significant variation of atmosphere condition. Therefore, every year's corrected data are subject to the change of natural environments, such as the clouding condition and wildfires. Besides, the image processing methodology varies every year, which directly affects the radiance data. Also, VIIRS sensor is less sensitive to lightings with high CCT than to those with low CCT.[22] Thus, it is possible that the radiance values after LED conversion were underestimated. Therefore, the results presented in Figure [3] and [4] should only be used for exploratory purposes. In future research, one can adopt different versions of processed VIIRS data, in which some algorithms are applied to filter out natural lightings from the environment.

Second, the data collected from citizen science projects were used with only minimal processing. This may pose problems as the raw data were not verified and tested. For a more rigorous study, steps such as reliability test and outlier detection can be applied to ensure the data quality. Also, instead of summarizing the data by year, the future study can consider aggregate data by year and month to address the effect of seasonal factors.

Lastly, more skyglow and light pollution data can be investigated for cities around the world that have implemented the LED street light conversion projects. Exploratory studies of this kind can provide preliminary insights for policymakers, urban designers, economists, and other researchers to investigate the association between urbanization, technology development, and light pollution.

[22] Suomi NPP VIIRS day-night band on-orbit performance (2013)

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Appendix

Timesheet

Date	Time	Hours	Task
07-26-2020	11:00 AM	10	(1) Background research (HPS and LED retrofit in US) (2) Identify three cities for investigation (project timeline) (3) Identify availible dataset (LED Project Report, Globe at Night, Cities at Night)
07-27-2020	11:00 AM	3	(1) Draft detailed research outline (2) Draft research proposal
07-29-2020	11:00 AM	3	(1) Process & run GaN data
07-31-2020	11:00 AM	3	(1) Find clear cities night image of Los Angeles (2) Review a paper that analyses the skyglow change of Tucson before & after led conversion (3) Install GDAL package (4) Research update1
08-02-2020	9:00 AM	10	(1) Background research on LED conversion project information in major cities in CA and AZ Decided to change cities to Los Angeles and Phoenix (2) Write and run script to parse light pollution Geotiff data for Los Aneles and Phoenix (3) Write script to output visualization for GaN data
08-03-2020	11:30 AM	2	(1) Write script to output visualization for radiance data - distribution & scatter plot
08-04-2020	11:00 AM	2	(1) Find clear cities night image of Phoenix (2) Finalize script files, output files
08-05-2020	10:30 AM	4	(1) Draft "literature review" and "methodology" paper section (2) Research update 2
08-06-2020	9:00 AM	2	(1) Record presentation videos and create presentation materials
08-07-2020	9:00 PM	3	(1) Draft "result" paper section (2) Finalize "literature review", "methodology" and "result" sections
08-08-2020	10:00 AM	4	(1) Draft "introduction", "discussion", and "appendix" paper sections
08-09-2020	10:00 AM	3	(1) Finalize and submit paper
	Total Hours		**49**