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Finding Darkness: A Case Study on the Light Polluting Effects of Regis University

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FINDING DARKNESS: A CASE STUDY ON THE LIGHT POLLUTING EFFECTS OF REGIS UNIVERSITY

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I. Introduction

"If the stars should appear one night in a thousand years, how would men believe and adore; and preserve for many generations the remembrance of the city of God which had been shown! But every night come out these envoys of beauty, and light the universe with their admonishing smile" (Emerson, 1836). Ralph Waldo Emerson published his essay, *Nature,* in 1836. During this era, Emerson's hometown of Boston, Massachusetts was lit by gas lamps at night. On a summer night in the city, one could walk along a Boston street, look up, and see the Milky Way arching across the sky. Today, Bostonians live under a hazy, yellow night sky. Only the brightest stars and planets are visible to the naked eye. With the bright lights common to all major cities, light has become a pollutant, a toxic fog that obscures starlight and eradicates the natural darkness of night. In his quote, Emerson expresses that if the stars only came out once in a millennium, humankind would not experience the wonder and inspiration of the universe. He remarks that he is grateful that the stars appear every night.

Sadly, for most of the world population, the stars do not come out every night. Light pollution, a term coined during the twentieth century, obscures our view of the stars and blocks the inspiration that it gives to humanity. It is estimated that eighty-three percent of the world live under light polluted skies. Ninety-nine percent of Americans live under light pollution (Falchi et al., 2016). Without the night sky, we lose an essential part of what it means to be human. In profound ways, our humanity is intricately bound to the night sky. Almost every culture on Earth has myths, legends, and stories about the

night sky. Our ancestors looked to the heavens for inspiration, wisdom, and peace in a world with many unknowns. The night sky is a right that every human should have access to.

As a child, I spent many summer nights outside gazing at the stars. My family would make pilgrimages to National Parks such as Great Sand Dunes, Rocky Mountain, Yellowstone, Arches, Grand Teton, and Death Valley. I would sit next to the campfire and look at the heavens, tracking satellites as they slowly pulsated across the sky and patiently wait for meteors to fall from space, burning trails of their brilliance into my vision. In these wildernesses, I could see the Milky Way splayed out across the sky, the Great Rift clearly juxtaposed with the bright galaxy. These moments gave me a deep appreciation for the power of the darkness. The night sky is both inspirational and humbling. It reminds me of the incomprehensible scale of the universe and the grandeur of wildernesses untouched by humans. After these trips, upon returning to the Denver suburbs, I would look up and be disappointed by the lack of stars. It was these experiences that opened my eyes to humanity's affinity for destruction of nature. Even though civilization does not pollute on purpose, industry and inefficient practices threaten the ecosystems of the world. I am eternally grateful for my experiences in the darkness, and I wish that everyone has a chance to see the unadulterated night sky. My goal in writing this thesis is to make the community aware of the detriments of light pollution—on people and the environment.

This publication is, foremost, a case study on the lighting practices of the Regis University Lowell Campus. The study analyzes the efficacy of campus lighting fixtures

in providing health and safety to students, faculty, and staff of the university. It also seeks to determine the extent of polluting light the campus generates. Finally, the study outlines techniques the university could employ to make lighting infrastructure safer, healthier, and more pleasing while still being dark sky friendly.

Definitions of Light Pollution

Light pollution is not limited to the yellowy haze that obstructs starlight. There are, in fact, four principle types of light pollution defined below (IDA, 2012).

1. Urban Skyglow – The dome of light that extends above and around urban areas, characterized by an increase in sky brightness. It is caused by unshielded, skyward directed light.
2. Glare – Bright lights that shine directly into people's eyes, reducing vision, and rendering depth perception impossible.
3. Clutter – Groups of glare-producing lights that further confuse people and even animals.
4. Light Trespass – Light directed into areas or regions where it is unwarranted and unwanted.

Urban skyglow is the most immediate and noticeable form of light pollution. It is a nuisance to stargazers and amateur astronomers and a downright obstacle for professional astronomers and astrophysicists. It is characterized by a light dome that surrounds cities and urban areas. Oftentimes, if one ventures to rural or wilderness areas, one can see the physical dome of light that surrounds cities. A system of roughly quantifying skyglow exists; the nine-point Bortle scale. A Class One Bortle sky has a

luminance of approximately 21.7-22.0 mag/arcsec^2 (an astronomical brightness unit). Class One skies are defined as "Excellent Dark-Sky Sites." The Milky Way and phenomena such as zodiacal light and airglow are clearly visible. Moreover, the Dark Rift region of the Milky Way is clearly contrasted against the backdrop of the Galaxy. On the other end of the scale, large cities feature Class Nine Bortle skies. Few constellation forming stars are visible. The only Messier object that can be seen is Pleiades. The luminance of the sky is 4.0 mag/arcsec^2. It should be noted that the unit of magnitude is inversely proportional to brightness. Thus, the brighter the object, the lower the magnitude.

Glare, the second form of light pollution, is caused by poorly designed light fixtures that shine directly into users' eyes, creating a blinding effect. Glare causes the pupils to contract, further reducing vision. Instead of aiding vision, lights that produce glare have the opposite effect. Research suggests glare-producing light fixtures pose a threat to security. The common notion that more light equates to more safety has been proven false in some cases. Glare causes a sharp contrast between brightly lit areas and shadows. Due to this high contrast, it is difficult for the human eye to see darker areas and potential threats hiding in the shadows. A 1996 report titled, *Preventing Crime: What Works, What Doesn't, What's Promising* found that "lighting is effective in some places, ineffective in others, and counterproductive in still other circumstances" in preventing criminal activity (Sherman et al. 1997). Light is necessary for safety, security, and productivity. But, poorly-designed light hinders progress in these areas. Instead, for lighting to fulfill its purpose, it must be well-designed and judiciously implemented.

Clutter is manifested when multiple glare producing lights are grouped in close proximity, across a singular field of view. Times Square in New York City or Tokyo's Shibuya Crossing are extreme examples of clutter. Multiple screens compete for attention and bright ornamental lights dazzle and confuse. Some humans are drawn to these marvels of commerce, yet other beings are overwhelmed. These flashy urban centers, while amazing works of art, harm the surrounding wildlife. In cities, clutter confuses birds, causing them to crash into buildings or other structures (Van Doren et al., 2017). Baby sea turtles, who depend on the soft glow of starlight reflecting off the ocean to navigate to the sea, are confused by clutter. Tragically, they may travel in the wrong direction and are eaten by predators or fall into storm drains (Silva et al., 2017). Clutter can also be reduced and even eliminated simply by putting thought into the design and spacing of light fixtures.

The fourth type of light pollution, light trespass, is light directed in places where it is unwarranted, unwanted, and unneeded. A good example is a neighbor's security light shining into your bedroom window. Light should not encroach on other people's home or places where it is a hindrance. With the proliferation of research that suggests that ambient bedroom lighting can lead to melatonin suppression, light trespass can even put people's health at risk (Zeitzer et al., 2000).

Detriments of Light Pollution

Animal Species

Despite the common belief that light pollution is something that only affects astronomers and stargazers, its consequences are far reaching. It has already been

outlined that glare and clutter affect birds and sea turtles, but almost every species on Earth is detrimentally affected by humanity's stray lights. A review article published in *Physiology and Behavior* asserts that artificial light at night acts as an endocrine disruptor in many animals and reduces overall fitness (Russart & Nelson, 2018). Another synthesis that reviewed hundreds of studies found that artificial light at night has a devastating effect on insects. The authors claim that insect populations are a good indicator of overall environmental health. Light pollution, especially the type generated by white LEDs, encroaches on insect habitats and can cause population reductions (Owens & Lewis, 2018). Light pollution may even alter the evolution of animal species. A review article published in *Frontiers in Ecology and the Environment* found that the presence of skyglow in urban areas influences gene flow, gene drift, and acts as an agent of artificial selection (Hopkins et al., 2018)

Science is just beginning to realize that light pollution poses a threat to the environment. There are many more experiments, studies, and reports that are beginning to uncover the damage our stray photons pose to animals and plants.

Human Health

Most land species (disregarding specialized cave organisms) have evolved under a periodic cycle of light and dark. This cycle never ceases, and organisms depend on it to regulate their physiological and psychological processes. The human species is no exception. There were no artificial lights (aside from fire) to work by at night. Present day technology allows us to stay up once the sun goes down. We stare at our screens and live under artificial lights long past dusk. For the darkness instils fear—fear of the

unknown. This fear kept our ancestors alive. Natural selection allowed for fearful humans to survive and prosper: those that ventured into the night or into dark caves were killed off by bears and other predators. Today, to combat this fear, we light our streets and do everything in our power to all but eradicate the night.

The natural light-dark cycle has been drastically altered. What once were roughly equal periods of dark and light has become mostly light. This constant bombardment of light is causing our natural circadian rhythm to fail. Health of the body and mind depends on a circadian rhythm tuned to the organic, periodic cycle determined by the rotation of Earth. Instead, the modern circadian rhythm is mis-calibrated by the lights that surround us. The average human spends one third of life in a state of slumber. Sleep is a process that is necessary, but little understood. Research is beginning to uncover the lasting damage lack of sleep can cause. Numerous studies suggest that sleep deprivation increases the risk of developing illnesses such as cancer and heart disease. Sleep deprivation is caused by many factors, including light pollution; but, exposure to unnecessary light plays a huge role in damaging the circadian rhythm (Reiter et al., 2012).

One mechanism that regulates the circadian rhythm is the melatonin cycle. Melatonin is a hormone secreted by the pineal gland that regulates the feeling of drowsiness, necessary for sleep (Reiter et al., 2012). Exposure to wavelengths of light, primarily blue, causes the suppression of melatonin leading to the feeling of wakefulness (Zeitzer et al., 2000). Evolutionarily, the reason is that during the day, humans are exposed to bright blue light from the sky. With the advent of modern lights and screens,

humans are exposed to blue light long past sundown. LCDs and other modern types of screens produce a spectrum of light with the highest peak at blue wavelengths. Moreover, Light Emitting Diodes (LEDs) produce harsh, bluish light. Exposure to blue light after the sun goes down suppresses melatonin so we no longer feel sleepy. As a result, people receive fewer hours of sleep, and insomnia and sleep deprivation are a plague of our productive society.

As stated earlier, sleep deprivation in humans increases the risk of mortality as a result of disease. A clinical review conducted by Erhard Haus and Michael Smolensky suggests that shift work, Artificial Light at Night (ALAN), and sleep deprivation constitute a greater risk for illness such as obesity, cancer, metabolic disorders, and cardiovascular disease (Haus & Smolensky, 2013). A study conducted in the year 2000 showed that human circadian rhythm is largely governed by melatonin, which is regulated by light (primarily blue light). This study, moreover, found that even small amounts of room light during the first six hours of night contributed to almost complete melatonin suppression (Zeitzer et al., 2000). The evidence presented in this study suggests that humans are extremely sensitive to ALAN and the circadian rhythm can easily be thrown out of balance by small levels of light. With the arrival of the LED, lighting efficiency has increased, but many LEDs are short wavelengths. High frequency light creates light with a lower color temperature, thus, bluer light. Even though LEDs reduce power consumption, they also induce melatonin suppression more than other types of light.

LEDs are sometimes considered a *miracle invention*. They allow for more light at a fraction of the cost. Moreover, LEDs produce very little heat and last thousands of hours longer than incandescent lights or other technologies. This industrial breakthrough has caused cities around the globe to implement LED technology into lighting infrastructure. In the long run, LEDs save money in energy, materials, and maintenance. Unfortunately, there is another cost. Urban skyglow has drastically increased since the installation of LEDs in major cities. Short wavelength white/blue light from LEDs contributes to skyglow much more than higher color temperature lights such as halogen or sodium bulbs. This meteoric rise in LED usage has caused an unprecedented obstruction of humanity's view of the night sky. Italian astronaut Samantha Cristoforetti photographed the city of Milan from the International Space Station. Milan recently made the transition from high pressure sodium streetlamps to LED luminaires. This change is clearly evident from space: the surrounding suburbs give off dimmer levels of red light from the sodium lamps while the city center shines a bright white. In a *New York Times* article, Brooklyn residents lament their annoyance of the overly bright, white LEDs that were recently installed along the streets. One resident, Joletta Benal, remarks, "It feels like I'm in a strip mall in outer space" (Renneisen, 2015). Blue-white light from LEDs worsen light trespass and wears on the nerves of citizens.

Security

One of the main purposes of lighting outdoor spaces at night is safety and security. Most people feel safe in the presence of bright lighting. Homeowners everywhere install bright floodlights to deter crime and prevent burglaries. Contrary to

popular belief, research indicates that brighter lights in larger quantities may not be the solution. In some cases, more light has the opposite effect—lights can attract criminal activity. A report titled *Preventing Crime: What Works, What Doesn't, What's Promising* found that in crime deterrence lighting helped in some cases, but in others it had no effect or even attracted it (Sherman, et al., 2000). The problem is not the presence of ALAN. Lighting is completely necessary for safety and security at night. It helps us find our way, enhances our vision, and facilitates travel otherwise impossible. The problem is in the poor design that plagues most light fixtures. Glare that shines directly into peoples' eyes causes the pupils to contract, thus, destroying night vision capabilities. Moreover, the sharp contrast between bright spotlights and dark areas allows criminals to easily hide in the shadows, effectively evading detection.

Solutions

The solution is simple: smart and thoughtful light design. Light fixtures should cater to the human eye, not simply flood as much light as possible into an area. To minimize glare, light sources should be diffused and directed in ways that do not shine directly into the user's eyes. Moreover, light should be directed only in places where it is needed to reduce light trespass. Groupings of multiple fixtures in a small area are often unnecessary and unwarranted. Clutter can be eliminated if the minimum number of lights are installed that still fulfill their intended purpose. Skyglow is caused by horribly-designed lighting fixtures that direct light straight up into the atmosphere. Shining light into the atmosphere is comparable to watering the driveway instead of the lawn: electricity is literally thrown away, carried into space by photons. Skyglow, and the waste

associated with it, is easily preventable with covers and shielding that redirect light downward where it is needed.

Light pollution is a complex problem; however, the solution is straightforward. Unlike toxins and other types of environmental pollutants, light pollution is stray photons that last for nanoseconds in the atmosphere. Mitigating light pollution is a community effort, but the best place to start is at the local level. Municipal building codes exist to create safe and hospitable buildings, infrastructure, and homes for residents. Lighting ordinances exist, but few include dark-sky friendly practices. Codes that do exemplify dark skies sometimes are not enforced. In order to limit light pollution so that our nights are safer, more sustainable, and healthier, cities should implement and enforce lighting ordinances that are International Dark Sky approved. The International Dark Sky Association (IDA) is a nonprofit organization that strives to reduce light pollution. The IDA employs leading experts to research and propose solutions to the growing threats associated with global light pollution. Currently, the text *Fighting Light Pollution*, written by scientists of the IDA, is the leading authority on design best practices for dark-sky friendly light fixtures. These best practices should be referenced when new lighting ordinances are drafted.

While it may seem daunting for cities to enforce new building codes for the protection of the night sky, it is completely possible. Proof of this innovation and community effort can be seen in the towns of Westcliffe and Silver Cliff. Situated in south-central Colorado, between the Wet Mountains and the Sangre de Cristo Range, Westcliffe and Silver Cliff are isolated communities, away from major cities, that are in

prime dark-sky territory. Prior to 2015, no ordinances in these towns regulated light design. Because of the effort of local stargazers and amateur astronomers, thousands of dollars were raised to retrofit light fixtures with dark-sky friendly shielding. Both towns then adopted comprehensive ordinances, regulating outdoor light fixtures. It took some coaxing and persuading, but the town residents followed the new codes and adopted friendlier lights for their homes. In 2015, both communities were awarded the IDA dark-sky designation. With work, education, and open dialogue, it is possible to make our cities friendly to the night sky, sustainable, and healthy. Then, perhaps Emerson's quote will ring true again: "But every night come out these envoys of beauty, and light the universe with their admonishing smile."

What do we lose when we lose the night, the darkness? To many, the gloom of the night represents the mouth of a cave of irrational fear, a black opening hiding the unknown. It is easy to reject this fear, to stay outside the cave in the soothing warmth and light. But those who venture into the mouth, those who embrace the darkness, the fear, find beautiful crystals and magnificent formations. Hidden behind the ugliness of fear, the night holds delicate treasures that fuel the human spirit.

To go in the dark with a light is to know the light.
To know the dark, go dark. Go without sight,
and find that the dark, too, blooms and sings,
and is traveled by dark feet and dark wings.

-Wendell Berry

The night sky is part of our heritage. We look to the sky with questions and receive prompt and complete answers. It tells us about the seasons, directions, and the universe. Ancient sailors would have perished at sea if the stars were not there for navigation. The annual location of stars was used to plan crops, harvests, and hunts. Myths, legends, and religions find their basis, their philosophies, in the night sky. Today, scientists look to the night sky to answer the most basic, yet profound questions. The universe holds answers to its origin, and the night sky leads to the inspiration needed to find them. There are seven natural wonders of the world, and yet, humanity has forgotten to include the eighth, the most important, the one right above us that remains obscured for 83% of humanity. The night sky belongs to humanity, it belongs to ecosystems, it belongs to the Earth. The time is now to protect it.

II. Case Study: Regis University Lowell Campus

The Regis University Lowell Campus is situated in Northwest Denver, just south of the Adams County border. The campus itself is situated 4.25 miles away from the city center of Downtown Denver, the largest light polluter in Colorado. The area surrounding Denver is a massive metropolitan area stretching from Boulder in the north, all the way to Centennial at the southern aspect. This metropolitan area has the effect of generating enormous amounts of light pollution. Within this area, the quality of the night sky never improves from a Bortle Class 5 (Falchi et al., 2016). Regis lies at the heart of this massive urban-industrial area. The night sky above our campus is classified as a Bortle 7. Although the campus is situated in an area with skies that are extraordinarily polluted, the lights on campus contribute to the overall light pollution of the area. The overarching goal of this thesis is to analyze the lighting infrastructure on the Regis Campus to determine how polluting it is. How much light pollution does our campus generate and how might we mitigate our polluting effects?

As an anchor institution in the community, Regis University seeks to be a positive agent for change and a community leader in social and environmental justice. The light pollution from our campus is harmful to students living in university housing, staff, the surrounding flora and fauna, and residents of the surrounding neighborhood. Since research is just beginning to uncover the harmful effects of light pollution, to uphold the values as an institution, Regis University should act to reflect upon our lighting practices and consider making updates for the good of the community. If universities and

community leaders make positive changes, others quickly follow suit. Our University has the potential to be a catalyst for dark sky practices that are the first steps to eliminating light pollution so that future generations of humans, animals, and plants can thrive.

Methods

To analyze light fixtures found on campus to determine the extent of light pollution the University generates, three experimental methods are used.

First, images of light fixtures around campus are obtained and the photographs are qualitatively analyzed to determine whether the lights contribute to the four principle types of light pollution defined in the introduction.

Second, a full-frame DSLR camera with a spherical fisheye lens is used to create 360-degree images of the campus at night. These panoramic views of the campus at night allow the visualization of any skyglow that our campus generates. The one problem with images from a spherical fisheye lens is that major distortion occurs in the field of view. To aid in qualitative analysis, the circular 360-degree images are converted to Robinson Projections to lessen the distortion of the fisheye lens. This has the benefit of allowing the viewer to perceive the buildings on campus in a natural way. Moreover, these images are quantitatively analyzed with computer software. Skyglow from light fixtures on the campus can be quantified by graphing the pixel value of the 360-degree image over a change in the azimuthal angle. These graphs allow for the direct comparison of skyglow at different directions in the sky.

Finally, an SQM-L (Sky Quality Meter) is employed to quantify urban skyglow generated by the campus. This instrument is useful because it allows for the comparison

of sky brightness from off campus and on campus locations. It also allows for a grid survey of sky brightness at various locations on campus to determine if certain lighting features noticeably contribute to skyglow. The interpolation tool in ArcGIS is also used to create an approximate map of sky brightness for campus.

Results

Analysis of campus light fixtures

The Regis Lowell Campus is brightly lit at night. Light fixtures on campus fit into two general categories, security lights and aesthetic lights. Security lights illuminate parking lots, walkways, and building entrances. Mostly, these lights are of practical design and illuminate target areas with bright, even light. Aesthetic light fixtures are used to highlight campus architecture, statues, and other artistic features of the campus. Each design is generally unique to the feature it illuminates. It is important to note that both categories of light fixtures are necessary for a safe and aesthetically pleasing campus. In the fight against light pollution, however, it is especially important for all lights to be well designed. Also, well designed lights improve upon safety and minimize environmental damages as well as negative health effects.

Campus Security Lighting

The most common security light found on Regis Campus is the acorn luminaire (below).

Figure 1: Acorn Light outside Caroll Hall

Figure 2: Acorn Luminaires near DeSmet and O'Connell Hall

These fixtures are a popular choice for walking paths and campuses. The problem is that they create all four types of light pollution defined in the introduction (IDA 2012). Although the acorn luminaires on our campus feature opaque tops, they lack any sort of shielding. Thus, a large percentage of the emitted light shines upwards into the atmosphere contributing to skyglow. Moreover, since the light is directed outwards at all angles, glare is produced. This glare makes it difficult to see in darker areas. In *Figure 2*, even though the walking path is fully illuminated, the high contrast from the glare creates a harsh shadow to the left. This creates a security challenge. It is easy for criminals to hide in the shadows to evade detection. Any pedestrian walking on the path is subjected to light shining directly into their eyes. This stimulates the pupils to contract and decreases low light vision.

The acorn luminaires exist in large quantities throughout the campus. There are locations that host multiple fixtures proximal to one another. This abundance is redundant and contributes to clutter. Since the acorn luminaires feature bright white bulbs, the output of a single fixture is sufficient for lighting a large area.

Moreover, there are locations on the borders of campus that feature acorn luminaires that shine onto neighbors' houses. These fixtures coexist with the cobra-head luminaires owned by the City and County of Denver. Acorn luminaires owned by Regis are unnecessary along these stretches of road and contribute to light trespass in the neighborhood. The houses along Lowell are bathed in the light from the acorn luminaires and the harsh white light seeps into unshaded windows. This is intrusive to the neighbors of the University.

Campus Aesthetic Lights

The Regis campus hosts a variety of statues and artistic works that are illuminated to highlight the beauty of the campus. Unfortunately, the lights that exist for this purpose are not the best in terms of light pollution. The worst possible light fixture for light pollution is an upwards directed floodlight. There are multiple artistic features on campus that are illuminated with bright spotlights that shine light directly into the atmosphere. In *figure 3*, three spotlights shine upwards to illuminate a statue outside the Felix Pomponio Science Center. These spotlights shine into the atmosphere, wasting light and contributing to skyglow. Moreover, they shine into pedestrians' eyes, effectively blinding them. Such bright lights are not necessary for this application.

Figure 3: Floodlights illuminating a statue

Figure 4 shows the centerpiece of Regis, Main Hall, illuminated by eight high output floodlights. These floodlights greatly contribute to skyglow. Since Main Hall is the trademark building of Regis University, it is understandable that planners would want to showcase this beautiful building at night. There are more effective ways of doing this that also preserve the nighttime environment. The first improvement would be to have building-mounted fixtures that shine downwards. This design measure eliminates the chance for skyglow production. Moreover, illuminating a building with floodlights is a brute force method and detracts from elegance. Dim accent lighting is aesthetically pleasing and highlights architectural features of a structure. Rather than illuminating the full façade, fixtures that illuminate lines of a building are more effective.

Figure 4: Main Hall, illuminated by eight high intensity floodlights

Analysis using all-sky images:

Figure 5 is an all-sky image taken from the intramural field. The spherical fisheye lens creates a three-dimensional image, displaying a field of view equivalent to half a sphere. With the lens pointed directly upwards, it creates a full hemisphere view of the night sky.

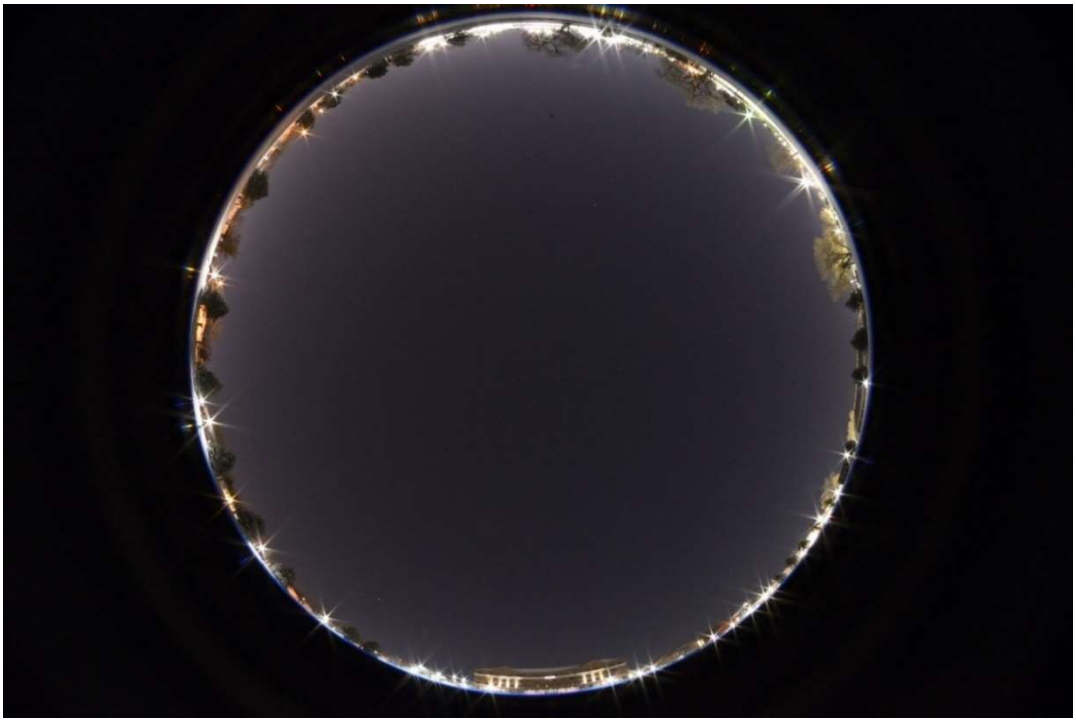

Figure 5: 360-degree view of campus at night. Taken from intramural fields

To aid in the visualization of the three-dimensional image, a Robinson projection of the all-sky image is created. This method of projection is used because it compromises between conformal and equal area methods to minimize distortion. In this image, it is immediately apparent that there are bright lights that shine outwards horizontally. This is an example of glare: the light is directed outwards and not downwards where it is needed. Moreover, in the eastern quadrant (middle left) of *Figure 6*, we see a cluster of bright

white lights from Parking Lot 6. The lights from Parking Lot 6 and Regis Square generate large amounts of glare and clutter. In the west (middle right) near Clarke Hall, there is less glare; however, it is still present. This photo was taken in the middle of the intramural fields, approximately 100 meters from the acorn luminaires along the walking path north of Clarke Hall. These light fixtures are far away from the lens; yet, the glare is tremendously visible. It is evident that the lack of shielding contributes to bad glare. Clutter is also maximized due to the sheer number of fixtures present. Most of the horizon in the Robinson projection is lined with light.

Figure 6: Robinson Projection of color image. 360-degree view of campus at night.

Figure 7 shows the same Robinson projection of campus but is in false color to allow the visualization of urban skyglow. In the southeast of the image (slightly left of center), the light dome from Downtown Denver is visible. In this image, the light dome of Downtown combines with a secondary dome of light produced by the fixtures of Parking Lot 6. Because of the sky brightness gradient that is created by Denver and the surrounding metro area, it is difficult to discern how much skyglow is actually produced by Regis Campus. This difficulty is addressed in the sky brightness map that follows this section.

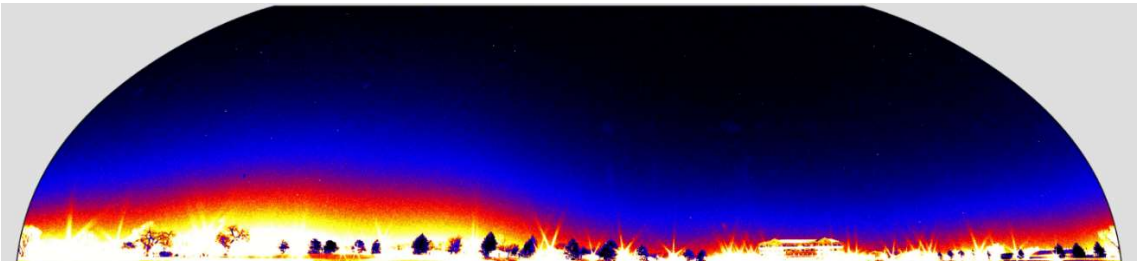

Figure 7: False color view.

Figure 8 is the three-dimensional view of Boettcher Commons (the quadrangle). Notice the dramatic lens flare in the upper left diagonal of the circle. Many of the security lights and acorn luminaires create lens flares resulting from the glare they produce.

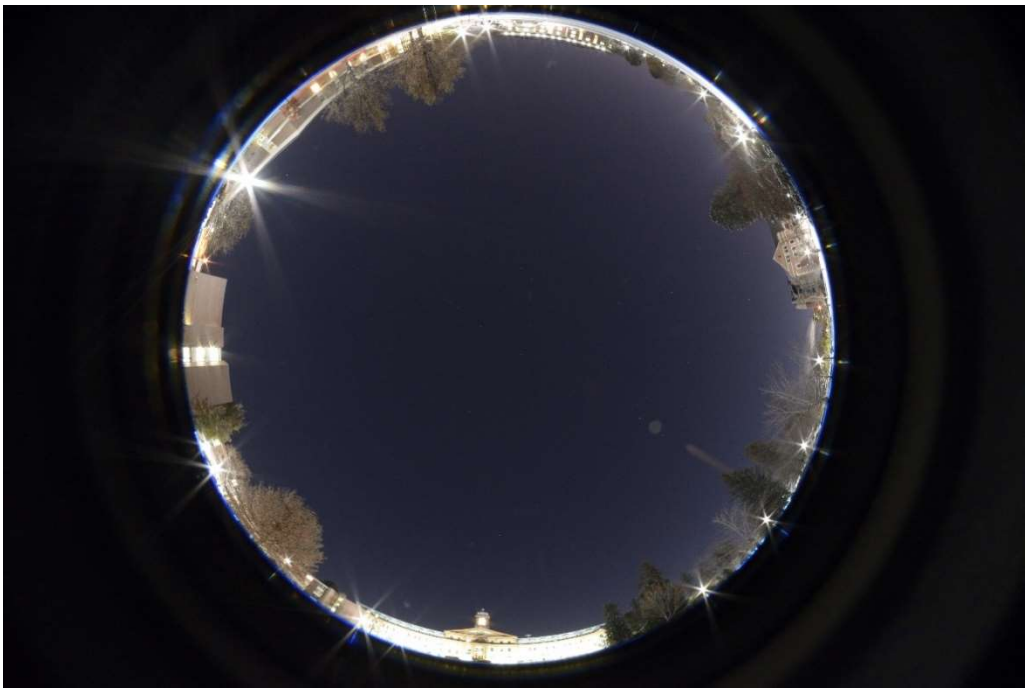

Figure 8: 360-degree view of Boettcher Commons

Figure 9 is the same 360-degree view transformed into a Robinson Projection. Main Hall is clearly visible in the north; the façade is incredibly washed out from the eight floodlights pointed upwards.

Figure 9: Robinson projection of Boettcher Commons

Figure 10 shows the quad projection in false color with a logarithmic scale to aid in the visualization of skyglow. The sky brightness, in all directions, is brighter near the horizon. In this image, we can see the sky brightness gradient from west to east. Directly west, the skyglow is lowest as the western suburbs of Denver near the foothills generate far less light pollution than the urban areas to the north, south, and east. Many acorn luminaires can be seen producing glare radiating in all directions. Glare is detrimental because it hinders human vision; light shining directly into the eyes causes the pupils to contract, thus, creating a counterproductive effect. Instead, light fixtures should be shielded to prevent light from emanating outwards and upwards.

Figure 10: Boettcher Commons false color image

The following three images were taken from Clear Creek Park, almost exactly one mile north of campus. Off campus locations were photographed to see if there was

obvious, highly visible light pollution generated by campus. *Figure 11* is the true color Robinson Projection taken from a field in the park. Regis Campus to the south is marked with a yellow arrow. From this image, any skyglow from campus blends with the skyglow resulting from the rest of the Denver Metro Area.

Figure 11: 360-degree color view of Clear Creek Park, North of campus

The false color image shows the same result. Here we see the sky brightness gradient resulting from the bright polluted skies of Downtown Denver in the east, with darker skies in the west. Regis does not appear to create an abnormal amount of skyglow in comparison to its surroundings.

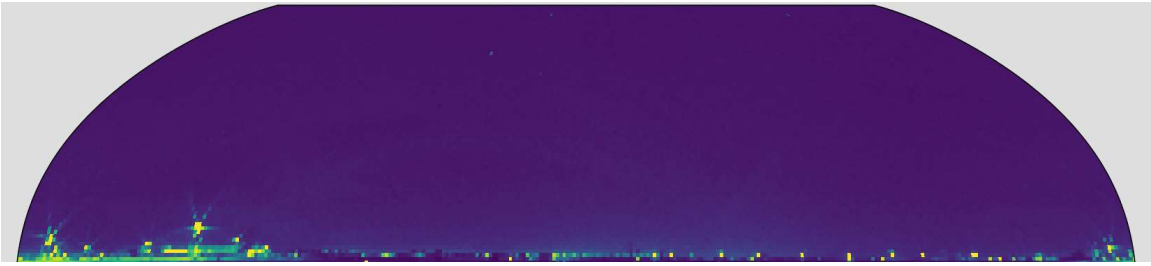

Figure 12: False color view from Clear Creek Park

Figure 13 is a close-up of the northern side of Regis Campus. The north façade of Main Hall is visible along with the bell tower of the Chapel. Because Main Hall is visible

from a mile away, it can be concluded that glare-producing light sources outside the building are illuminating the façade (the north side of Main Hall is not illuminated by floodlights). There are multiple acorn luminaires situated on this side of Main Hall; it is hypothesized that these contribute to the illumination. Moreover, the bell tower of the Chapel is highly illuminated (left of Main Hall) in the image. Upwards facing spotlights are used to illuminate the bell tower. This aesthetic feature of campus should be showcased; however, the current lighting solution contributes to skyglow.

Figure 13: Close-up of Northern aspect of Campus. Taken from Clear Creek Park

Quantitative Analysis of All-sky Photographs

The three-dimensional images shown previously allow for the qualitative visualization of light pollution generated from our campus. The data stored in these images can be analyzed with quantitative methods. ImageJ, an open-source scientific image analysis

tool, is used to create a series of graphs that plot pixel value versus azimuthal angle at a specific direction. In an urban setting, the sky does not have a uniform brightness. Instead, there is some variation that depends on the azimuthal angle. In the case of Regis Campus, the darkest region of the sky is the zenith (directly overhead) and the brightness increases dramatically towards the horizon. This variation of brightness also depends on the cardinal direction. *Figure 14* shows a graph of the sky brightness as a function of azimuthal angle corresponding to the four cardinal directions. This data was obtained by averaging the pixel value for several lines contained in a 'pie slice' (*Figure 15*).

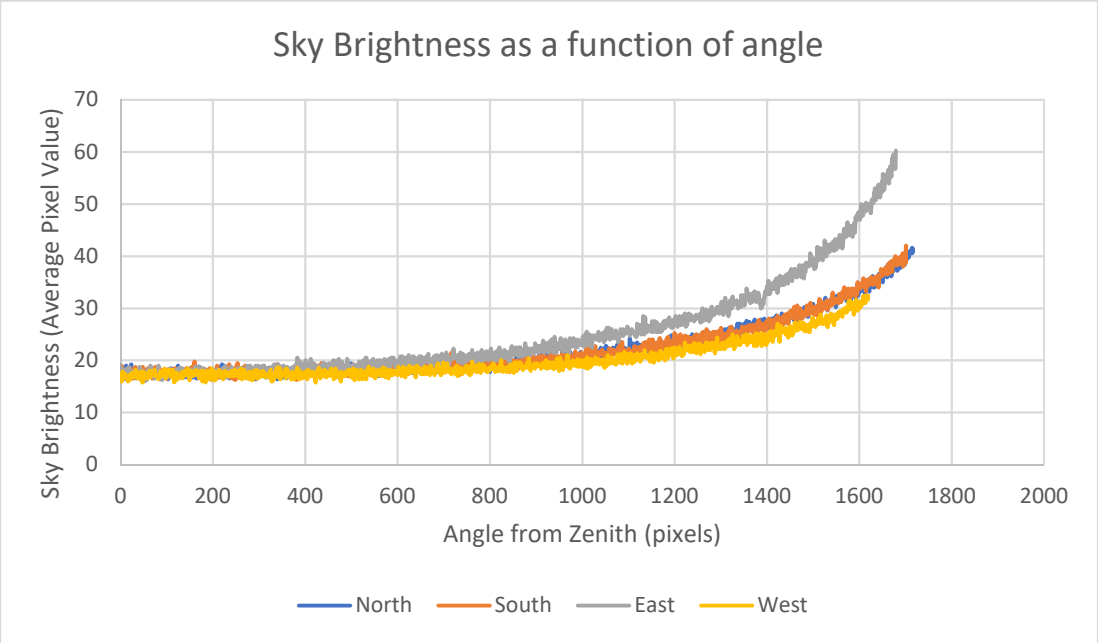

Figure 14: Graph of Sky Brightness as a function of Angle for the cardinal directions

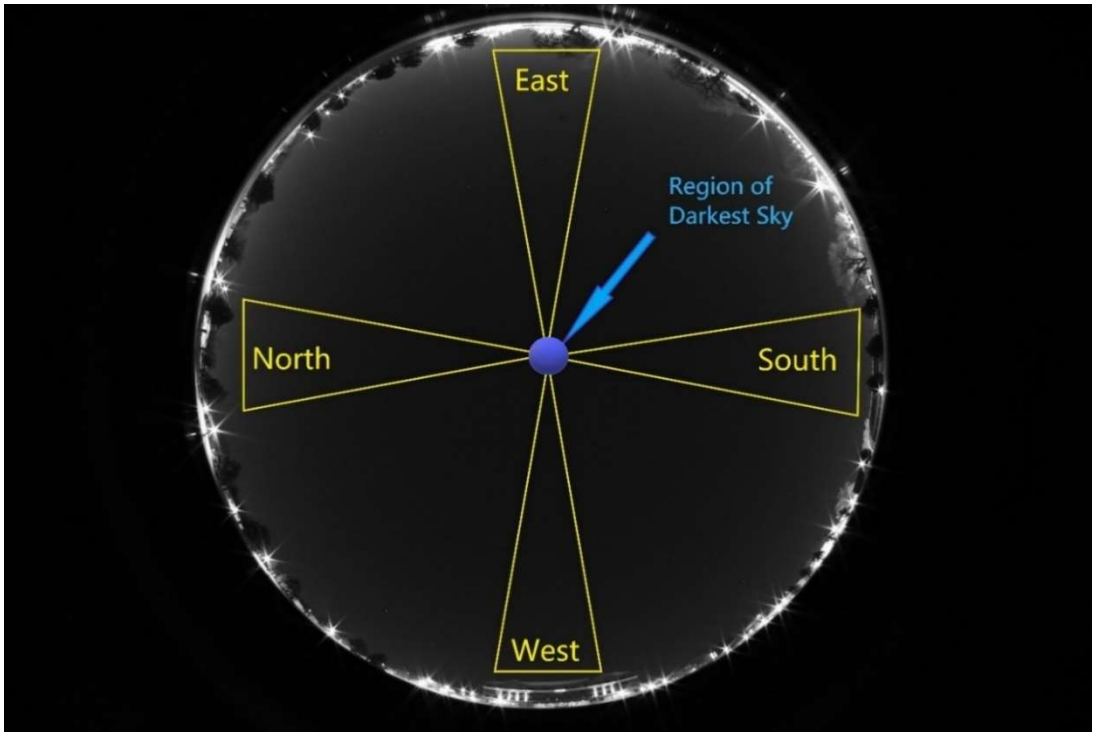

Figure 15: Areas within the yellow 'slices' show the data areas. A series of lines originating from the blue circle were drawn within the slices. The pixel brightness was plotted as a function of angle from the zenith.

Interestingly, the maximum skyglow was lowest above Regis in the west and highest immediately above Parking Lot 6 in the east. It is hypothesized that the sharp increase in sky brightness to the east is a product of the skyglow from the Northern limit of Downtown Denver as well as the lights above Lot 6. The sky brightness in the west (above campus) is the lowest magnitude. The lower skyglow in the west is a result of there being fewer urban centers than in the east. It can be concluded, however, that there are skyglow producing light fixtures in the west because of the increase in sky brightness. Whether the increase in sky brightness close to the horizon is from the campus is inconclusive. It is impossible to draw any conclusions about skyglow produced by the

campus because skyglow from the rest of Metro Denver interferes with the analysis. What is visible, however, is that in all four directions, sky brightness increases as azimuthal angle decreases (approaches the ground). The zenith is the darkest region of the sky, and the skyglow can be quantified as greatest near its source.

Sky Brightness Survey

Light fixtures that shine light upwards and outwards create skyglow. This increase in sky brightness can be measured directly with instruments that can detect luminous flux, such as a digital camera. In this case study, a Sky Quality Meter (SQM-L) is used because of its portability and instantaneous measurement. To obtain an accurate representation of sky brightness values on campus, locations were chosen with (a) special distributions that are relatively uniform and (b) adequate separation from bright lights that effect the measurement of sky brightness. Three SQM measurements were taken at each location. Because the SQM measures sky brightness on a logarithmic scale, the average brightness values were linearized to allow for ease of comparison.

It should be noted that this survey is a representation of sky brightness values experienced by a person standing in the observation location. Light fixtures create spheres of light because of atmospheric scattering and diffraction. Location to glare producing light fixtures strongly affects the local sky brightness as measured by the SQM. A survey that accurately measure the total sky brightness produced by the campus would involve taking measurements at an elevation above the light sources. Recently, drones have been employed to create accurate light pollution models. This survey yields a

lot of information; however, it does not examine every intricacy of the light pollution generated by the campus.

In the survey, not surprisingly, the brightest locations on campus were recorded in parking lots. Lot 7 and Lot 6, (map number 18 and 17, respectively) were the two brightest parking lots. The sky brightness measured in Lot 7 was 15.33 mag/arcsec^2. Lot 6 was measured to be 15.35 mag/arcsec^2 (recall that on the magnitude scale, the lower the value, the brighter the sky). The sky brightness of Lot 7 is over 40 times brighter than the value of the darkest measurement on campus, the middle of the quad (map number 1). Regions that are sufficiently separated from light sources yielded measurements that were closer to the average sky brightness for the North Denver Region, approximately 18.55 mag/arcsec^2 (Falchi et al. 2016). Still, the dimmest measurement was 17.35 mag/arcsec^2, which is still over three times brighter than the North Denver average. From this survey of sky brightness, it can be inferred that the nighttime environment of the Regis Campus is brighter than the surrounding locations.

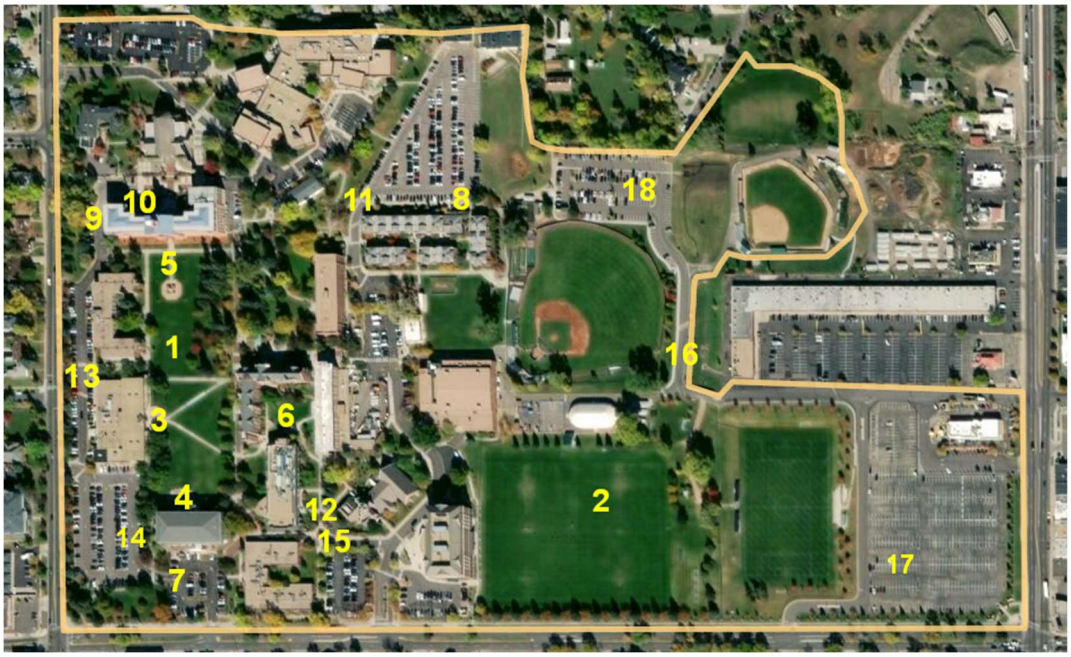

Figure 16: Map of SQM observation locations. Numbers correspond to figure 18 graph. Numbers are in ascending order of darkest measurement to brightest.

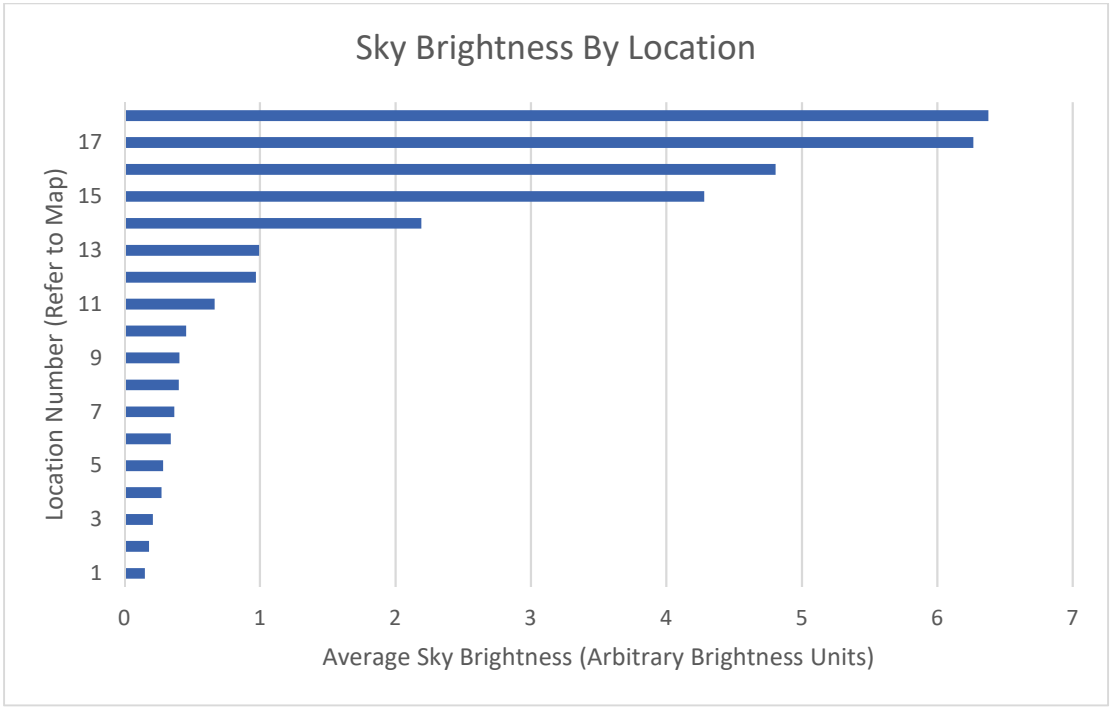

Figure 17: Sky brightness for each location on map.

Interpolative Map of Campus Sky Brightness

Interpolation is a tool used in Geographic Information Science to create a continuous raster map of a phenomenon from discrete, measured values. In geospatial interpolations, the computer program estimates the study value for all points in space from experimental values. To supplement the sky brightness survey and provide a visual representation of urban skyglow produced on Regis Campus, a map of sky brightness was created using the interpolation tool in ArcGIS. The observation locations with the brightness values were plotted on a map and the Spline with Barriers interpolation method was used to estimate a continuous raster of the sky brightness on campus. Spline with Barriers was chosen as the interpolation method because even though skyglow is unaffected by the presence of barriers, this method allowed for the raster estimate to be extended outwards to the border of campus. This interpolation method was compared to others such as Kriging and Inverse Distance Weighting and the results were similar.

From the resulting map, it is obvious that the brightest locations on campus are the parking lots. What is interesting, however, is that the residential parking lot (Lot 5) is the dimmest parking lot on campus. This is one of two lots that are open twenty-four hours a day. The brightest lots on campus sit empty between the hours of 11:00PM and 6:00AM while being lit with bright floodlights. Not only is this a waste of energy, lighting an empty lot serves no purpose and does nothing but generate light pollution. This practice is analogous to watering a sidewalk.

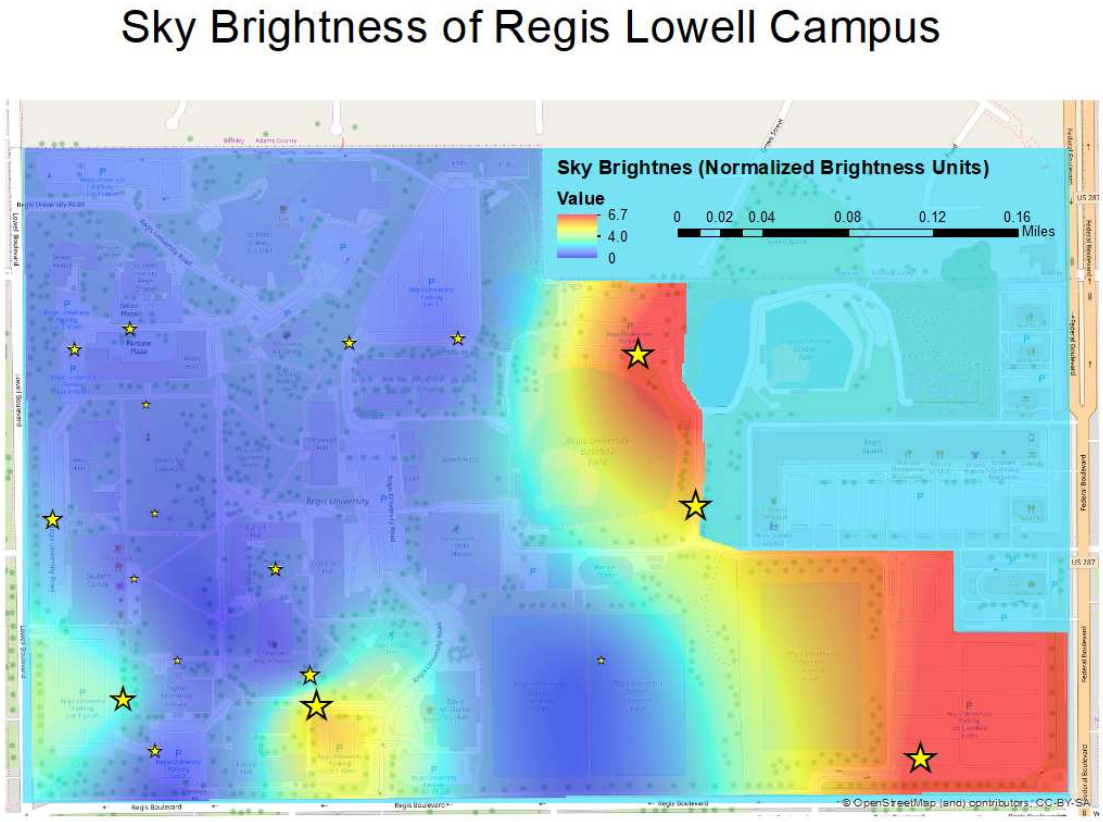

Figure 18: Interpolative Sky Brightness Map of Campus. Star icons correspond to observation locations. Large stars correspond to high brightness values.

Recommendations for the Mitigation of Light Pollution on Regis Campus

For any college campus, the nighttime environment of the grounds and buildings is extremely important. Students, faculty, and staff want to feel safe when travelling to dining halls, evening classes, residences, offices, and places of study. Parents want to send their students to universities that offer the utmost safety for their children. Brightly lit nighttime environments are perceived by most people as safer than dark areas. Most people do not think about the environmental and human health repercussions of poorly designed and polluting light fixtures. Thus, designers and planners prioritize safety and

security and use bright lights on most campuses. The problem, however, is that perceptions about safety are usually based on intuition rather than reason. Humans naturally fear the dark; thus, technology is employed to eradicate it. Problems arise because often, greater amounts of light at night exacerbate the issues we seek to solve.

Whether or not artificial lighting at night prevents crime is an ongoing debate. Owners of homes and businesses employ security lights and motion-activated floodlights to deter crime. On the surface, this makes logical sense: criminals naturally want to avoid detection; thus, they will keep away from brightly lit areas. Criminologist Ken Pease, however, explains that lights can attract criminals. In highly lit areas, criminals do not need to carry flashlights, which attract attention to themselves. Moreover, opportunistic crime can occur because lights allow thieves and burglars to easily scope out targets (Pease, 1999).

Nighttime lighting for security prevention is a complicated problem. Some cases show that it is beneficial, but others suggest that it can do harm. This disagreement in conclusions can also be found in quantitative studies conducted on streetlights and crime. Studies conducted prior to 2000 show that light sources inhibit crime (Soper, 2015). Recent studies, however, show no correlation between artificial light at night and reduced crime (Steinbach, Perkins, & Tompson, 2015). A systematic review of streetlights and crime rates was carried out by the Swedish National Council for Crime Prevention in 2007. In this review, of the eight American cities that were analyzed, four (Atlanta, Milwaukee, Kansas City, and Fort Worth) showed decreases in crime rates accompanied by light infrastructure improvements. The others (Portland, Harrisburg, New Orleans, and

Indianapolis) showed null effects (Farrington & Welsh, 2002). Crime is complex, and many factors contribute to its occurrence. Humans are unpredictable, and it is difficult to discern whether the presence of security lighting influences crime rates. In most cases, factors such as location and police presence have a greater effect than lighting infrastructure on crime rates.

Whether crime rates are affected by the presence of artificial light at night seems to be situationally dependent—just because lights prevent crime in one place does not mean they will elsewhere. Perhaps it is more important to consider individuals perceptions of safety, which is as important as crime prevention. Cultivating a sense of safety in the community is important for human welfare and mental health. Most people would agree that brightly lit areas feel safer than dim areas and research agrees. A 2017 study found that parking lots with high photopic illuminance are perceived by humans as safer (Rea, Bullough, & Brons, 2017). The same study found that lights that render true color accurately are perceived as safer than zones that add colored glow. This may come as bad news for dark-sky friendly endeavors, but it is important to acknowledge. Dark-sky activists need to recognize that people naturally fear the dark. It is difficult to change a view so deeply entwined in society. Instead, dark-sky practices should work to increase human health, protect the environment, save energy, all while maintaining a perception of security.

This list of objectives seems difficult, if not impossible to achieve; but, with the right tools and techniques, dark skies and safe streets are both attainable. It all comes back to intelligent design of lighting infrastructure. The issue of light pollution is not

black and white; thus, the solution cannot be dichotomic. It is not a matter of choosing between lighting our streets and cutting power to all nighttime lights. Instead, it is necessary to recognize that artificial light at night is an integral part of our cities. Then it is up to everyone to make informed and intelligent decisions about how we light the night.

From the data obtained during the case study of Regis University Lowell Campus, I have formulated three principle recommendations for reducing light pollution while maintaining safety and security:

1. Add shielding to all acorn luminaires
2. Eliminate the use of spotlights for aesthetic purposes
3. Add light timing systems to parking lots that are not used after hours.

This list consists of actions that are simple, cost effective, and unobtrusive to students. I understand that each solution may pose difficulties to facility management and may not be possible due to financial and logistical constraints. I do hope, however, that the solutions create a campus-wide dialogue about our impact on the community and the environment and how we could improve our sustainability.

1: Shield Acorn Luminaires

Acorn Luminaires are the most common light fixture on the Regis Lowell Campus. Unfortunately, these light fixtures are the worst in terms of efficiency and dark sky friendliness. They shine light in all directions contributing to all four

types of light pollution. To decrease light pollution and avoid wasted electricity, simple metal shields could be added to existing acorn luminaires. These shields would substantially reduce the campus's contribution to urban skyglow. Moreover, since light is directed downwards where it is needed, glare and light trespass are reduced.

Rather than replacing each luminaire, simply adding shielding to existing fixtures is cost effective and beneficial to students, faculty and staff, and the surrounding flora and fauna.

Figure 19: Properly shielded acorn luminaires reduce all four types of light pollution. (Graphic from Athens-Clarke County)

2: Improve Aesthetic Lighting practices

Any light that shines into the atmosphere produces skyglow, but spotlights and floodlights are the worst. These fixtures do not diffuse light, and when directed upwards, create a large amount of skyglow. To reduce the incredibly wasteful effects, it is recommended that any aesthetic lighting that features upwards shining spotlights should be replaced with better alternatives. For example, in *Figure 19*, the spotlights illuminating the statue shine upwards at an angle. The light is harsh, and it shines directly into the eyes of passing pedestrians, contributing to glare. As an alternative, a light could be mounted on the side of the nearby Pomponio Science Center, directed downwards onto the statue. Moreover, a light diffuser could be added to the fixture to reduce glare.

Figure 20: Statue illuminated by three high output floodlights

Aesthetic lights that are redundant should also be pared down. For example, there is a large amount of clutter present outside DeSmet Hall (*Figure 21*). This light is unnecessary and distracting to students passing by. Moreover, this excess light can have hypothetical drawbacks to the health of students. High amounts of light trespass shine into the windows of students living in this dorm building. Even with the venetian blinds Residence Life provides, light still leaks into the rooms. My sister, Emily, is a resident of DeSmet Hall. I asked her if light from the acorn luminaires shined into her window. She replied, "Yeah, even with the blinds drawn, some light shines through the window and onto the wall near my bed. Sometimes, when I'm not tired, this is distracting, and it makes it hard to fall asleep." She also told me, "A girl down the hall bought blackout curtains, even though they are not allowed, so she can sleep at night."

Figure 21: Redundant accent lighting outside DeSmet Hall

3. Employ Timing Systems

In the Sky Brightness Survey, it was found that the two brightest locations on campus were Lot 6 and Lot 7. These two parking lots feature bright, short wave light fixtures that substantially increase the sky brightness in their vicinity. The problem, however, is that overnight parking in Lot 6 is prohibited. Residential students are required to park in Lot 5 during nighttime hours. Lot 6 remains lit *even when they are empty*. The practice of lighting empty parking lots is wasteful and unnecessary. Thus, I recommend that light fixture timing systems be installed in lots where overnight parking is prohibited. This would save energy and reduce light pollution.

III. Conclusions

Despite its damages to human health, the ecosystem, and nighttime security, light pollution is perhaps the easiest environmental contaminant to mitigate. Unlike pollution involving toxic chemicals, light pollution is erased instantaneously with the flick of a switch. The obstacle to dark skies, however, is not artificial light at night. Modern civilization depends on artificial light sources for a variety of reasons. Technology has given humans the means to defy evolution and physiology and become nocturnal, if we so choose. The modern way of life is sustained because people work in the nighttime hours. Business does not start at dawn and end with dusk. Day and night still oscillate back and forth, but our post-industrialized lives operate on a continuous line. I think that it is safe to hypothesize that great contributions to knowledge and humanity occur late into evening hours. Many people use the phrase "Carpe Diem" as a mantra for productivity. A phrase used not as frequently, "Carpe Noctum," also permeates our society. In a world so obsessed with immediacy and production, "burning the midnight oil" is acceptable and even encouraged.

Thus, it is impractical to suggest a fundamental restructuring of the way society functions. As long as technology exists, humans will depend on artificial light at night. But a beneficial facet of technology is that our electronics are becoming increasingly efficient and better designed. Moore's law states that the number of transistors on a microchip doubles close to every two years. Technology is always evolving to better serve humans and hopefully the environment. The good news is that lighting technology

can be adapted to create safety in our cities while still being efficient and dark-sky friendly. Outdoor lighting companies are now offering fixtures that contain the IDA seal of approval. For a light fixture design to become certified by the IDA, it must minimize glare, clutter, light trespass, and skyglow. Moreover, the bulbs must be of a color temperature above 3000K. This color temperature was chosen because it minimizes circadian disruption and the environmental impacts short wave, low color temperature light creates.

The detrimental effects of light pollution have been well documented; but, there is so much more at stake. The psychological, spiritual, and humanistic effects are just as catastrophic. Since the dawn of the first civilizations, humans have looked at the stars for inspiration, guidance, and awe. Staring at the expanse of the night lends an appreciation for the vastness of the universe and the wonder it contains. The radiance of the Milky Way is enticing and horrifying in a wonderful way. Staring at the nearest star, Proxima Centauri, and realizing that it still takes the fastest entity in the universe, light, 4.22 years to reach the Earth, one can appreciate how vast existence really is. Space is a void; yet, our galaxy and the 200 billion to 2 trillion galaxies in the observable universe are packed with brilliant stars, structures born and raised from tenuous gas, planets, and dust.

Carl Sagan said, “We have begun to contemplate our origins: starstuff pondering the stars; organized assemblages of ten billion billion billion atoms; tracing the long journey by which, here at least, consciousness arose” (Sagan, 1985). To simply stare into the sky at night is to experience the universe on a fundamental level. Science and reason, but also feeling, thrive in the presence of wonder. The night sky is a headwater of

wonder, a mysterious grotto from which an endless stream of questions arises. Despite the intricacies of life on Earth, it is necessary to realize that everything began with space. The night sky is a window into our origins. When we pollute the sky with stray photons, we close ourselves off to wonder, to inspiration. When the stars are hidden behind the yellow, hazy veil of skyglow, the spring of questions dwindles to a trickle. The majority of children growing up today live under the veil, and it is becoming worrisome. What will happen to science and art if the muse of the night sky disappears?

What do we lose when we lose the night sky? The answer is different for everyone, but one thing is clear—dark skies are a collective necessity. The night sky is a basic right every person should have access to, and it is up to local communities to take it back. Because of the current lack of education and awareness regarding the Dark Sky Movement, national action would be difficult. As a result, it is more productive to start with local communities. Westcliffe and Silvercliffe, Colorado have shown us that collective action to mitigate light pollution is entirely possible. Residents of the Wet Mountain Valley realized that the sky was under siege by poorly designed lights. Community members joined together and convinced their fellow citizens to activate changes to the way they lit the city at night. Because of their perseverance, these two mountain towns are IDA certified dark sky locations. This achievement is amazing.

Westcliffe and Silvercliffe should be a model for positive changes to lighting infrastructure. If anchor institutions such as hospitals, universities, schools, and municipalities strive to light more effectively, others will follow suite. Trend setting is a powerful means to induce positive effects. A world with untainted night skies is within

our grasp; imagine walking the streets of Downtown Denver and being able to see the Milky Way. Most movements for change start with small steps and grow with increasing awareness. Large scale, systematic progress is possible, but incredibly difficult. Local communities have the power to take small steps for improving lighting design and reducing light pollution. Even if lighting ordinances are not passed immediately, individuals and groups can take their own steps to make our skies darker. It is human nature to follow trends and believe in popular opinions. Everywhere I look, at least in Colorado, it is trendy to experience wilderness and untainted nature. I think most people agree that the night sky is beautiful. The next step is to help people realize that there are simple steps everyone can take to limit light pollution and the harmful effects it causes.

The rhetoric in our language tells us to look to the light for answers. We praise people for being *bright*. The quintessence of living is to reject the darkness, the evil, the fear, and the uncertainty. I propose a new paradigm shift—a restructuring of the psyche. To embrace the wonder of the dark, it is necessary to remove the negative adjectives and connotations from the word *darkness*.

LEAVES of poplars pick Japanese prints against the west.
Moon sand on the canal doubles the changing pictures.
The moon's good-by ends pictures.
The west is empty. All else is empty. No moon-talk at all now.
Only dark listening to dark.

-Carl Sandburg

All horrible things we picture in the dark are simply not associated with the darkness. No, horror and fear are products of uncertainty rather than the darkness itself. So, what do we find in the darkness? “Only dark listening to the dark.” If we look carefully enough, what we find is truly beautiful.

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