# Autonomous UAV-Assisted Light Pollution Mapping

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# Contents

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# Abstract

Night skies, pristine for millennia, are plagued by ever-increasing light pollution — hindering the quality of astronomical research, harming human health, and eliminating a source of inspiration and heritage to human civilizations. To enable effective solutions for combating light pollution, efficient mapping of the night sky's brightness must be realized. The current and most widespread method of surveying the night sky involves traversing through the desired area of surveillance and gathering measurements with a handheld Sky-Quality Meter (SQM), a tedious, time-consuming, and inconsistent process. With the development of unmanned aerial vehicles (UAV) allowing advanced customizability and capabilities, this study focuses on characterizing a streamlined methodology of mapping light pollution using this technology. A quadcopter UAV incorporating previously developed SQMs is customized optimally to collect sky brightness measurements. A Crossfire radio for maximum range, low kV motors for efficiency, and a Pixhawk flight controller enabling autopilot capabilities were used. Autonomous flight paths are mapped using the Mission Planner software, enabling data collection in remote areas, including forests, mountains, and aquatic bodies. Time and location of each SQM measurement are matched via a GPS device attached to the UAV system. Data were collected in areas of Cleveland National Forest, then analyzed and mapped with Python. In contrast to manual sky brightness measurements, this work shows the implications of utilizing a UAV system to survey vast expanses of the night sky efficiently. The practicality of our gradient-

colored maps created via Python allows appropriate measures and solutions for combating light pollution to be identified.

# 1. Introduction

## 1.1 The Importance of Dark Skies

Until only recently, humans have only known clear and dark skies throughout history. Thousands of stars visible to the naked eye were a source of inspiration for the most revolutionary advancements in philosophy, literature, art, and science, telling a rich and extensive story of humanity's history and heritage.

Simultaneously, others have long sought to illuminate the night for other various benefits – improved visibility, increased safety, and extended productivity during the night. However, with the proliferation of electric lights, there has been an unintended consequence: the onset of light pollution.

Light pollution is defined by the International Dark-Sky Association as "the inappropriate or excessive use of artificial light" [1]. Further organization categorizes light pollution into glare, skyglow, and trespass. Glare refers to the excessive brightness caused by light sources that cause visual discomfort. Skyglow is the glow effect that can be seen in populated areas, being the combination of all the reflected light and upward-directed lighting escaping up to the sky. Light trespass is the unwanted light that enters one's property. All types of light pollution are frequently encountered by many people, whether it is in large metropolitan areas, or more rural areas. Because of light pollution, more than 80% of the world's population is polluted with artificial light, with one-third of humanity not being able to see the Milky Way galaxy at night [2].

Light pollution generated by electric lights has detrimental effects on human health as well. Humanity evolved on this planet with reliable cycles of “light” and “dark”. The integration of light into what has always been darkness at night disrupts our natural circadian rhythm, or the internal cycle synchronized with our biological clock with the day-night cycle [3]. Our circadian rhythm is controlled by the hormone melatonin, and secretion of this hormone is suppressed when we are exposed to light at night, specifically blue and white light that mimics what we experience under the daytime sun. This disrupts our health, exemplified by the fact that exposure to artificial light at night has been linked with an increased risk for all types of cancer.

## 1.2 Current Survey Methodology

In order to combat the threats of light pollution, proper surveys of night sky brightness must be conducted.

The Visible Infrared Imaging Radiometer Suite (VIIRS) aboard satellites created in collaboration with the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) satellites takes daily measurements of sky brightness [4]. However, much of the word remains unmapped, and the nuances in the change of light pollution in many areas cannot be shown.

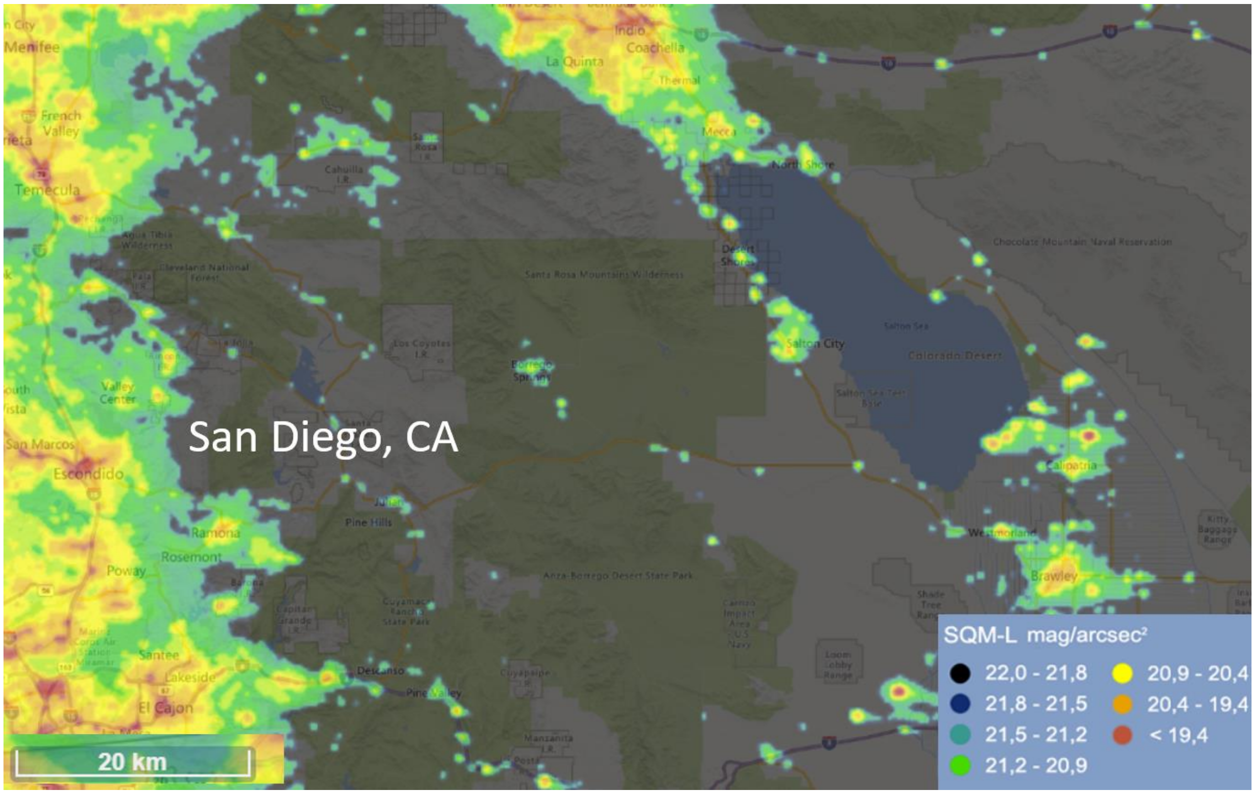


Figure 1. A sky-brightness map of Southern California, U.S.A., overlaid on a Google Maps base created with VIIRS 2021 data. Grey areas without color, including Cleveland National Forest, Anza-Borrego Desert State Park, and Chocolate Mountains, are unmapped. Background overlay image copyright 2019 Google, INEGI, used with permission.

Due to the low-resolution measurements taken by the VIIRS, light pollution measurements are also taken manually. The most common and widespread method used to manually survey the night sky involves traversing to the desired destination, pointing a handheld Sky Quality Meter (SQM) toward the sky, and recording the reading displayed on the SQM. This instrument allows the brightness of the sky to be quantified, taking measurements in magnitudes per square arcsecond. Measurements are taken in a range of 16.00 to 22.00 magnitudes per square arcsecond, with 16.00 representing a bright sky and 22.00 representing a dark sky. In perspective, the large, urbanized area of Los Angeles would have readings ranging from 17.00 to 18.00, while readings at Death Valley would range from 21.00 - 22.00.

The Unihedron company develops Sky Quality Meters, with different models built to serve different purposes. All handheld models require one to point the meter directly at the sky’s zenith to measure the sky's brightness.

## 1.3 Research Objectives - Integrating Unmanned Aerial Vehicles

The tedious process of manual sky brightness measurements hinders the amount of data that can be collected. This method of survey also severely limits the areas of data collection to be confined within traversable terrain. We address this issue by integrating an unmanned aerial vehicle system to conduct sky brightness surveys autonomously, bolstering the efficiency and practicality of this process. Although unmanned aerial vehicles have been tested for aerial imaging, taking sky brightness measurements directly has not yet been tested [5]

Unmanned Aerial Vehicles (UAVs), also known as “drones”, are defined to be any remotely piloted aerial vehicle with no humans on board. In recent years, UAVs have become increasingly more advanced and customizable. Parts have become smaller and more lightweight, reducing a UAV’s overall build weight, and increasing performance. Payloads can be customized, allowing drones to be tailored to the exact specifications required by the user. With specialized software, autonomous flights are now possible, eliminating the need for continuous human piloting. These advancements have made

UAVs a valuable tool in many fields, including cinematography [6], national defense [7], scientific research, and more. In addressing the advancements for sky-quality surveys, fabricating a UAV system incorporating autonomous capabilities while collecting sky brightness observations is a viable method for further development.

Utilizing UAVs for conducting light pollution surveys offers several advantages over manual data collection. First and foremost, they are significantly faster and more accurate. At high altitudes, physical barriers such as trees, hills, and other natural features are not a hindrance. Furthermore, computers can control drones with much more accuracy than humans, enabling consistent mass data collection that is easily replicable and applicable in any location with calm weather. Using UAVs also addresses a safety concern posed by manual data collection. Since sky-quality surveys must be done at night, surveyors may face visibility issues and encounter wildlife, an obstacle overcome by UAVs.

Furthermore, drones can operate over locations unreachable by foot or rugged terrain (mountains, forests, aquatic bodies, hills, etc.) without putting human researchers at risk. In addition to addressing another safety concern, it also enables surveys to be conducted in locations previously inaccessible, opening the doors for further refined light pollution mapping and research.

For the aforementioned advantages, this research concentrates on fabricating a UAV system that can efficiently conduct comprehensive light pollution surveys, with collected data easily analyzable via mapping programs created via Python.

# 2. Methodology

## 2.1 UAV Design and Construction

We begin by determining the size of our drone that allows efficient transport versatility, and compatibility with software. Our build is based on a quadcopter model for efficiency and control. We chose a 450 mm wingspan, providing an optimized balance of size, weight, and customizability, with trussed arms and two drone plates that allow the mounting of components. We then chose our flight controller with autopilot capabilities. Pixhawk 6C was picked, being the newest in a long lineup of autonomous-flying-enabled flight controllers by supporting autopilot firmware. The Pixhawk 6C bundle includes a GPS and power distribution board, both of which we use as well. For the motors, we prioritized efficiency. With a low current-to-voltage ratio, a low Kv rating of 925 indicating a high-torque output for large propellers needed for our UAV, the Velox 2812 925 Kv motor was chosen. Accompanying the motors, electronic speed controllers (ESCs) are needed to regulate the current flowing into the motors. 4 ESCs, each withstanding 35A of sustained current, are chosen. A radio is also needed so our controller and drone can communicate. Seeking a range of several kilometers, the Crossfire Micro TX with the RadioMaster TX-16S is most suitable. It boasts a 100-km maximum range and a user-friendly interface. Next, we need propellers large enough, so the motors stay under their 50% maximum speed to lift the drone. We decided to use 10” x 4.5” propellers for this reason. The battery also requires careful consideration in terms of size and weight; for our purposes, an 8200-

mAh battery was ideal, as its mass would not exceed the 10-kilograms of maximum thrust that our drone can output. Finally, to comply with federal law, a strobe light is attached to the bottom of the drone so that its location is visible from the ground. An FAA-certified light is mounted to the bottom of the drone using Velcro.

Figure 2: Drone after completed construction. Top and side view.

### 2.1.1 Sky Quality Meter Integration

To take sky brightness measurements, we incorporate a sky quality meter to the UAV system. Using the SQM LU-DL, our system can collect data autonomously at set periods while also recording the time and temperature. A USB port allows for easy download of the collected data. The included proprietary software, Unihedron Device Manager, allows a straightforward setup process and accessible data viewing. To integrate the sky quality meter with the drone, a bracket is designed to house the meter and attach to the drone. The mount uses a clamp design, with a bolt that runs through the mount as well as the drone to secure it tightly. It was designed and modeled in SolidWorks, then 3D printed on a Prusa i3 MK3S using PLA (polylactic acid) material. The rigid mount also allows for the sky quality meter to always point straight up, eliminating human variability in the data collection process.

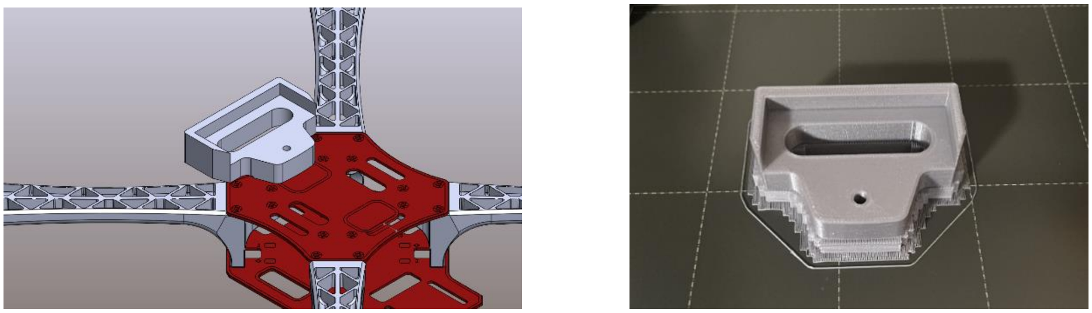
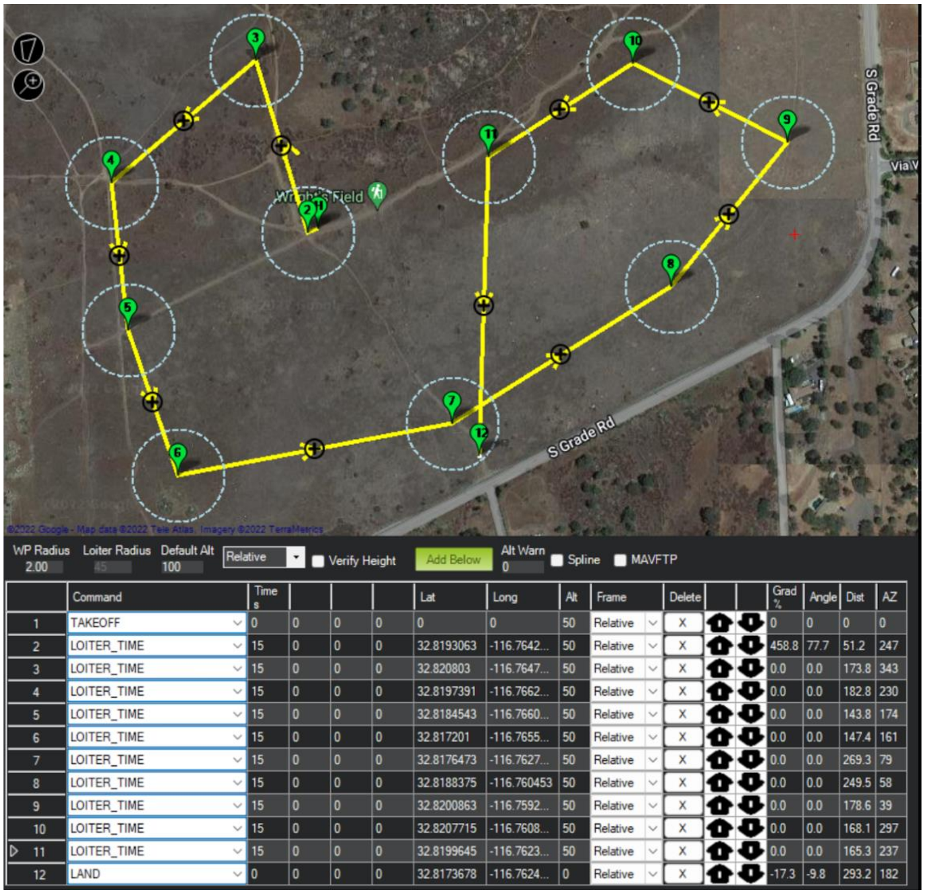

(a) (b)

Figure 3: (a) CAD (computer-aided design) file of the SQM mount before 3D printing. Simulated and designed specifically to fit the UAV. (b) Completed SQM mount post-3D printing.

## 2.2 Software for Autonomous Capabilities

With the UAV system constructed, we now incorporate it with the software Mission Planner, where all autonomous capabilities are configured. Mission Planner's interface allows straightforward flight planning. Through the Command section, "waypoints" are set. Waypoints map the exact flight takeoff and landing locations and decide the UAV's altitude and loiter duration at each location.



WP Radius 2.00
Loiter Radius 45
Default Alt 100
Relative
☐ Verify Height
Alt Warn 0
☐ Spline
☐ MAVFTP

| | Command | Time s | | | | Lat | Long | Alt | Frame | Delete | | | Grad % | Angle | Dist | AZ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | TAKEOFF | 0 | 0 | 0 | 0 | 0 | 0 | 50 | Relative | X | ⬆ | ⬇ | 0 | 0 | 0 | 0 |
| 2 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.8193063 | -116.7642... | 50 | Relative | X | ⬆ | ⬇ | 458.8 | 77.7 | 51.2 | 247 |
| 3 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.820803 | -116.7647... | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 173.8 | 343 |
| 4 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.8197391 | -116.7662... | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 182.8 | 230 |
| 5 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.8184543 | -116.7660... | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 143.8 | 174 |
| 6 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.817201 | -116.7655... | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 147.4 | 161 |
| 7 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.8176473 | -116.7627... | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 269.3 | 79 |
| 8 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.8188375 | -116.760453 | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 249.5 | 58 |
| 9 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.8200863 | -116.7592... | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 178.6 | 39 |
| 10 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.8207715 | -116.7608... | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 168.1 | 297 |
| ▷ 11 | LOITER_TIME | 15 | 0 | 0 | 0 | 32.8199645 | -116.7623... | 50 | Relative | X | ⬆ | ⬇ | 0.0 | 0.0 | 165.3 | 237 |
| 12 | LAND | 0 | 0 | 0 | 0 | 32.8173678 | -116.7624... | 0 | Relative | X | ⬆ | ⬇ | -17.3 | -9.8 | 293.2 | 182 |

Figure 4: A complete flight path mapped on Mission Planner software. Green points on the map represent waypoints, where each are specially set for either takeoff, loiter, or land. Background satellite image copyright 2019 Google, INEGI, used with permission.

For each location where data is to be collected, we set a loiter point where the UAV would remain for 15 seconds. It is synchronized with the sky-quality meter, which we set to take a measurement every 15 seconds as well, guaranteeing that one measurement is taken at every loiter point. We go through this process at every location we survey, setting waypoints loiter points, and altitude.

To retrieve data, we attached a Global Positioning System device onto the bottom of the UAV. Real-time location is tracked via the SilverCloud application on a cellphone, and the measurements' time measured from the Unihedron Device Manager is matched with the UAV's position at any time.

## 2.3 Test Flights and Adjustments

With autopilot capabilities allowed by the flight controller Pixhawk 6c, fine-tuning is not necessary, as compared to manual flying. The UAV's pitch, roll, and yaw, controlling stability and balance, automatically calculates and self-adjusts accordingly.

To test the UAV system over various terrains while mimicking real-world situations, we decide to conduct our night sky surveys at the Cleveland National Forest in San Diego, California. Efforts are underway to designate the Descanso Ranger District of the Cleveland National Forest as an International Dark-Sky Park [8]; a process where sky brightness measurements across vast amounts of land are required. Therefore, testing at the Cleveland National Forest best mimics the real-life applications of our UAV system. Furthermore, the wide variety of different terrain across the Forest allows implications for different flying scenarios to be situated, with irregular terrain and varying altitudes.

### 2.3.1 Altitude and Range Test

Before official test flights, confirmations of our drone's maximum abilities must be realized. The UAV system's altitude and range are tested; a flight path with an altitude of 100 meters, loitering at a stationary point for 15 seconds, and distance of 1 kilometer is written and flown. The UAV system successfully completes the flight and records the sky brightness.

### 2.3.2 Ma Awa Tar Viejas Camper Park

The first test flight is conducted at the Ma Awa Tar Viejas Camper Park, a location with relatively flat terrain and little to no obstructions. A zig-zag flight pattern is utilized to test the UAV's mobility to change directions. The total distance of this test flight spanned approximately 0.7217 kilometers at an altitude of 50 meters above relative terrain.

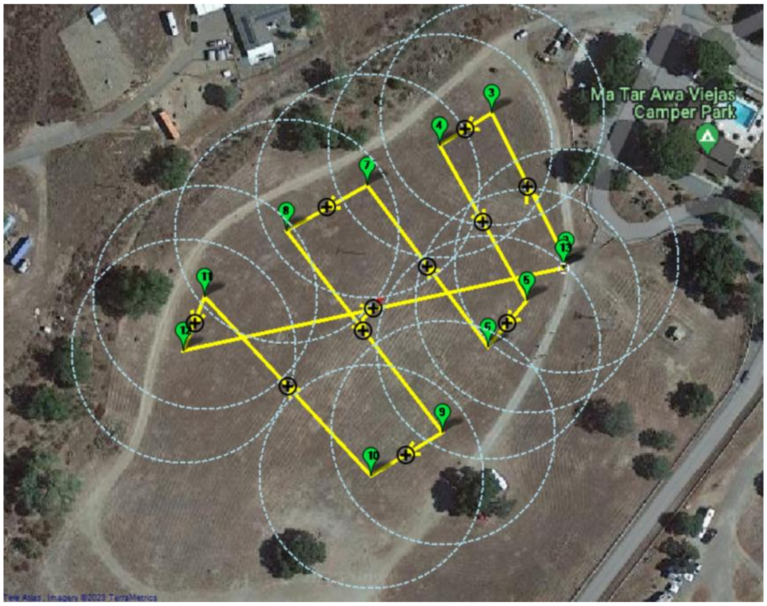


Figure 5.1: Ma Tar Awa Viejas Camper Park flight path for autonomous survey on Mission Planner software. 11 loiter points are used. Background satellite image copyright 2019 Google, INEGI, used with permission.

### 2.3.3 Wright's Field

The second test flight is conducted at Wright's Field. Through this test, more mountainous terrain is tested against the UAV system. The land features more trees and more frequent change in altitudes from hills and slopes. The total distance of this test flight spanned approximately 2.2548 kilometers at an altitude of 50 meters above relative terrain.

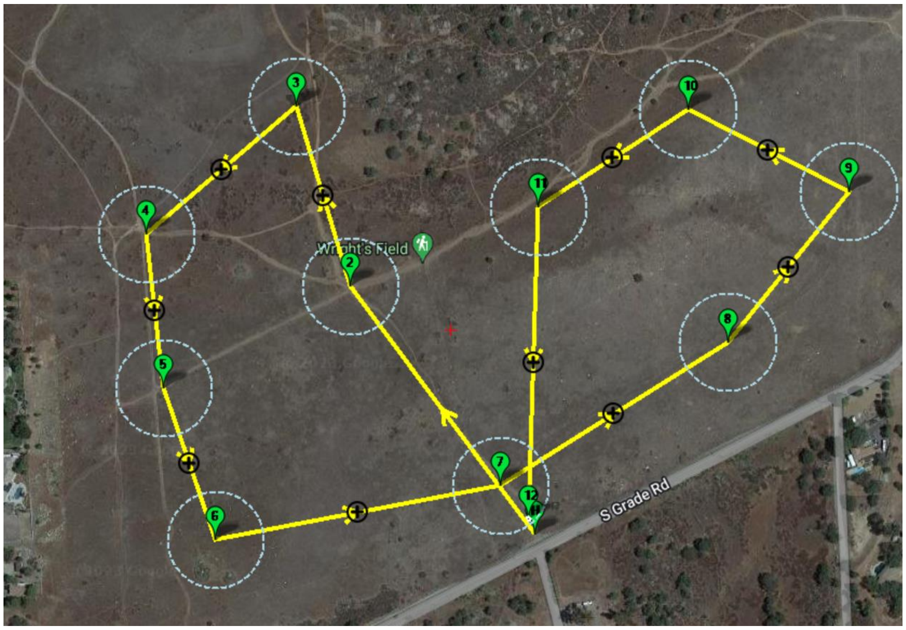


Figure 5.2: Wright's Field flight path for autonomous survey on Mission Planner software. 10 loiter points are used. Background satellite image copyright 2019 Google, INEGI, used with permission.

### 2.3.4 Mount Laguna

The third and final test flight is conducted in the Mount Laguna area. The terrain features highly forested and mountainous land, replicating the most extreme of conditions for conducting surveys. Furthermore, this test shows the radio communication's ability to withstand obstructions from trees and buildings. The total distance of this test flight spanned approximately 6.5913 kilometers at an altitude of 100 meters above relative terrain.

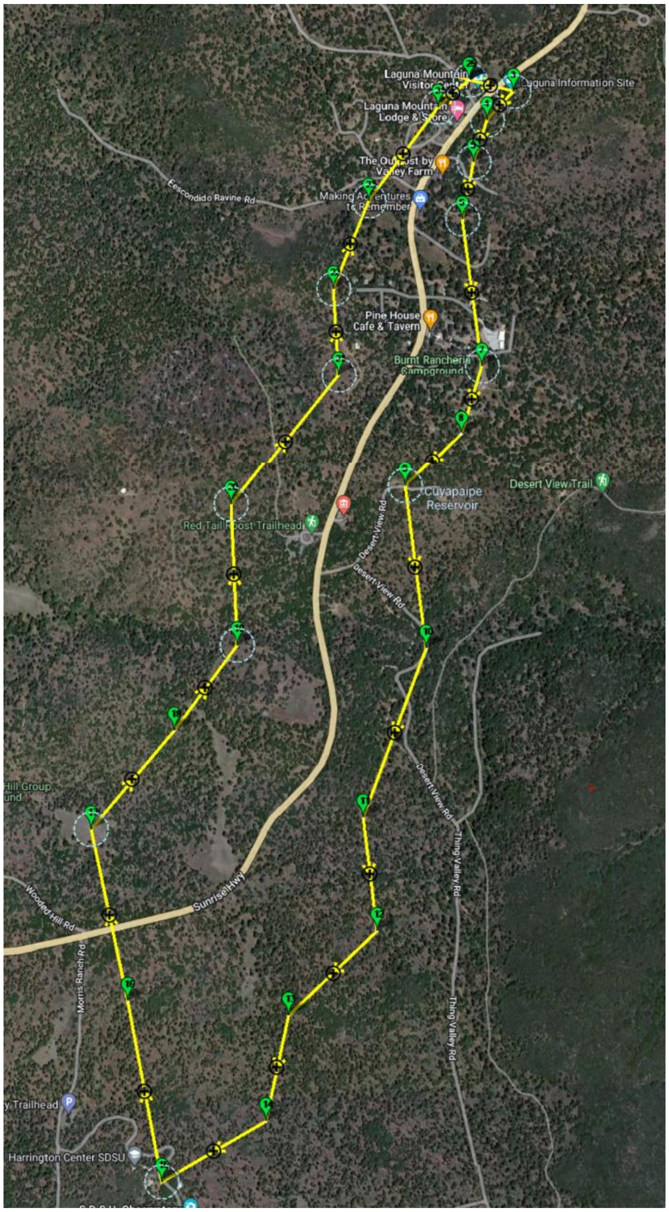


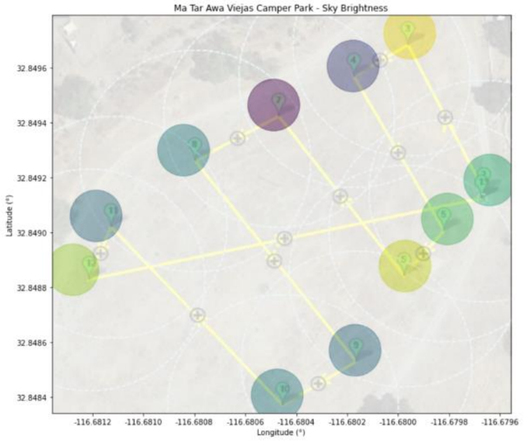
Figure 5.3: Mt. Laguna flight path for autonomous survey on Mission Planner software. 23 loiter points are used. Background satellite image copyright 2019 Google, INEGI, used with permission.

# 3. Results

## 3.1 Gradient Light Pollution Maps

For the quantified sky brightness measurements to be comprehended, collected data is graphed and overlaid on a satellite image of the location. Data collected by the SQM LU-DL provides the time in PST when the measurement was taken, the sky brightness reading in magnitudes per square arcsecond, and temperature at the time. After matching each data point to the real-time GPS location of the UAV system, the exact location of where the measurement is taken can be found.

Graphs are created via Python in this study. Each measurement is graphed to fit the exact location with longitude and latitude coordinates retrieved from the flight paths.



(a)

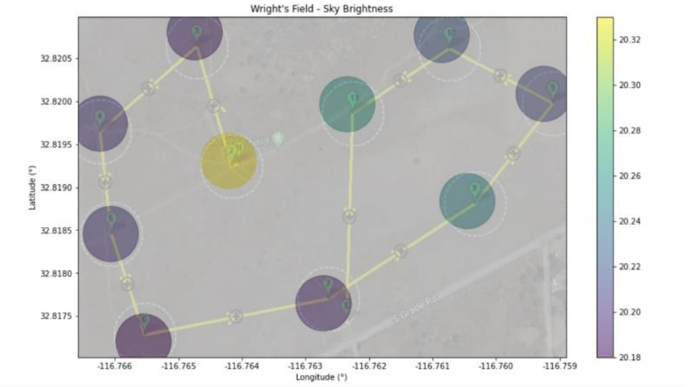
| Ma Tar Awa Camper Park | | | |
|---|---|---|---|
| Reading Number | Time (PST) | Reading (mag/arcsec$^2$) | Temperature (°C) |
| 2 | 11:54:32 PM | 20.46 | 5.4 |
| 3 | 11:55:17 PM | 20.51 | 5.8 |
| 4 | 11:56:17 PM | 20.40 | 6.7 |
| 5 | 11:56:47 PM | 20.47 | 7.0 |
| 6 | 11:57:02 PM | 20.50 | 7.7 |
| 7 | 11:58:02 PM | 20.37 | 8.7 |
| 8 | 11:58:32 PM | 20.43 | 9.3 |
| 9 | 11:59:01 PM | 20.42 | 9.5 |
| 10 | 11:59:54 PM | 20.43 | 9.3 |
| 11 | 12:01:02 AM | 20.42 | 9.3 |
| 12 | 12:01:47 AM | 20.49 | 9.3 |

(b)

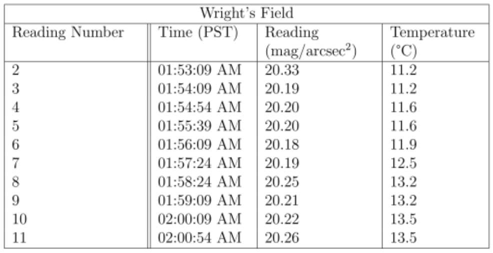
Figure 6.1: (a) Map of the variation of sky brightness over Ma Tar Awa Viejas Camper Park overlaid on satellite image. Measurements spread through a scale of gradient colors

indicate the sky brightness, with violet being the relative brightest and yellow being the relative darkest. Background overlay image copyright 2019 Google, INEGI, used with permission. (b) Chart of all data collected on the Ma Tar Awa Camper Park test flight. Reading number can be corresponded with the location of each measurement in Figure 5.1 (a).

Measurements from this test flight varied with no particular pattern. This can be attributed to the fact that the test flight covered a relatively small area.



(a)

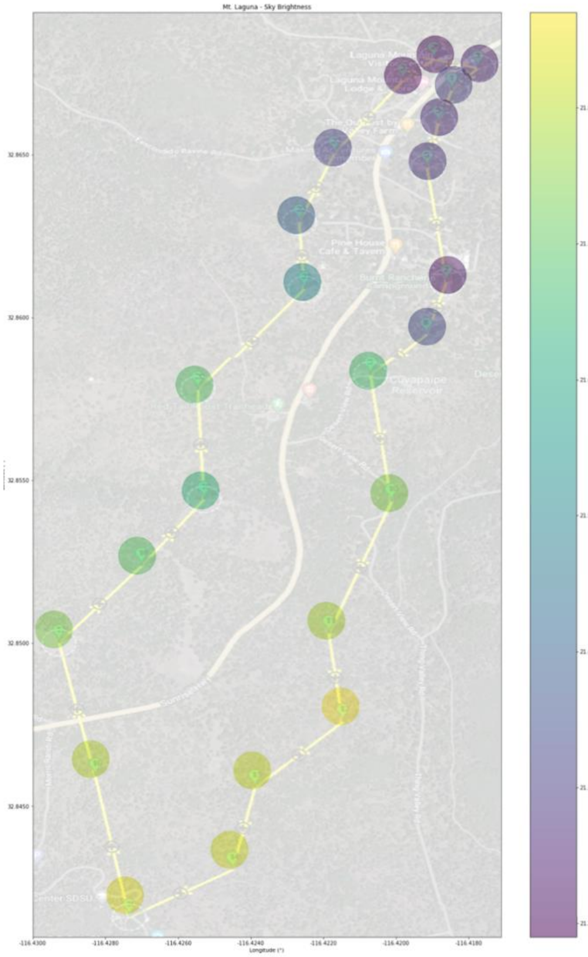


| Wright's Field | | | |
|---|---|---|---|
| Reading Number | Time (PST) | Reading (mag/arcsec$^2$) | Temperature (°C) |
| 2 | 01:53:09 AM | 20.33 | 11.2 |
| 3 | 01:54:09 AM | 20.19 | 11.2 |
| 4 | 01:54:54 AM | 20.20 | 11.6 |
| 5 | 01:55:39 AM | 20.20 | 11.6 |
| 6 | 01:56:09 AM | 20.18 | 11.9 |
| 7 | 01:57:24 AM | 20.19 | 12.5 |
| 8 | 01:58:24 AM | 20.25 | 13.2 |
| 9 | 01:59:09 AM | 20.21 | 13.2 |
| 10 | 02:00:09 AM | 20.22 | 13.5 |
| 11 | 02:00:54 AM | 20.26 | 13.5 |

(b)

Figure 6.2: (a) Map of the variation of sky brightness over Wright's Field overlaid on satellite image. Measurements spread through a scale of gradient colors indicate the sky brightness, with violet being the relative brightest and yellow being the relative darkest. Background overlay image copyright 2019 Google, INEGI, used with permission. (b) Chart of all data collected on the Wright's Field test flight. Reading number can be corresponded with the location of each measurement in Figure 5.2 (a).

Measurements from this test flight show that the sky brightness increases as one moves due east.



| Mt. Laguna | | | |
|---|---|---|---|
| Reading Number | Time (PST) | Reading (mag/arcsec$^2$) | Temperature (°C) |
| 2 | 11:59:01 PM | 21.20 | 9.2 |
| 3 | 11:59:58 PM | 21.24 | 9.2 |
| 4 | 12:01:12 AM | 21.30 | 9.2 |
| 5 | 12:02:15 AM | 21.26 | 9.2 |
| 6 | 12:03:21 AM | 21.28 | 9.2 |
| 7 | 12:04:57 AM | 21.21 | 9.2 |
| 8 | 12:05:44 AM | 21.33 | 10.4 |
| 9 | 12:06:59 AM | 21.67 | 10.4 |
| 10 | 12:07:31 AM | 21.75 | 10.4 |
| 11 | 12:08:45 AM | 21.79 | 10.4 |
| 12 | 12:09:58 AM | 21.87 | 10.4 |
| 13 | 12:10:53 AM | 21.82 | 10.4 |
| 14 | 12:11:49 AM | 21.83 | 10.4 |
| 15 | 12:12:28 AM | 21.85 | 9.6 |
| 16 | 12:13:55 AM | 21.80 | 9.6 |
| 17 | 12:15:04 AM | 21.75 | 9.6 |
| 18 | 12:15:42 AM | 21.70 | 9.6 |
| 19 | 12:16:35 AM | 21.64 | 9.6 |
| 20 | 12:17:10 AM | 21.69 | 9.6 |
| 21 | 12:18:27 AM | 21.51 | 9.6 |
| 22 | 12:19:01 AM | 21.39 | 9.6 |
| 23 | 12:19:54 AM | 21.31 | 9.6 |
| 24 | 12:21:29 AM | 21.19 | 9.6 |

Figure 6.3: (a) Map of the variation of sky brightness over Mount Laguna overlaid on satellite image. Measurements spread through a scale of gradient colors indicate the sky brightness, with violet being the relative brightest and yellow being the relative darkest. Background overlay image copyright 2019 Google, INEGI, used with permission. (b) Chart of all data collected on the Mount Laguna test flight. Reading number can be corresponded with the location of each measurement in Figure 5.3 (a).

Measurements from this test flight show an apparent change in brightness; as one moves due south, the sky is increasingly darker. This result is expected, since this test flight covered the largest area of land in respect to the previous test flights.

## 3.2 Discussions and Further Applications

As light pollution continues to worsen, it is imperative that we understand its changes over time in a comprehensive and succinct manner. In the current situation where many locations around the world remain unmapped, the outcomes of this study show that technological developments in a UAV-assisted sky surveying system presents a resolution to address this issue. The UAV system we developed can be used by scientists to efficiently gather data on light pollution. Further implications can reach local governments and legislators to better comprehend the threat of light pollution and how it continues to evolve over time. Meaningful legislation can be enacted, further preserving the valuable dark skies that we have treasured throughout human history.

The developments we explored in this study lay the foundation for novel research in vast fields of science to be conducted. Studies on light pollution's effect in the atmosphere at varying altitudes, and correlations between sky brightness and wildlife behavior are studies that be directly be elaborated upon through our UAV system.

Efficient mapping as investigated in our work can help us further comprehend the potentially far-reaching effects of light pollution. By addressing the problem of light pollution, we will not only improve the quality of our nightscape but protect the health and wellbeing of both the people and the natural world.

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