

Photometry of Celestial Fireballs Using a Portable All-Sky Camera

by

Luke Galbraith Russell

Submitted in Partial Fulfillment of the
Requirements for the Degree

Bachelor of Arts

Supervised by
Dr. Jed Rembold

Department of Physics

Willamette University, College of Liberal Arts
Salem, Oregon

2018

Presentations and Publications

L. Russell, Photometry of Celestial Fireballs, Poster Presentation at Linfield College (April 2018)

L. Russell, Photometry of Celestial Fireballs, Oral Presentation at Willamette University, SSRD (April 2018)

L. Russell, Photometry of Celestial Fireballs, Oral Presentation at Willamette University, Research Seminar I: Status Report Presentation (December 2017)

L. Russell, Photometric Analysis of Earthbound Fireballs, Oral Presentation at Willamette University, Advanced Techniques in Experimental Physics: Senior Proposal Presentation (March 2017)

Acknowledgments

I would like to thank the following professors for writing me letter of recommendations and for their own respective contributions:

- Dr. Jed Rembold for dealing with all my stupid questions regarding life and this thesis.
- Dr. Rick Watkins for being pretty dang funny.
- Dr. Daniel Borrero for forcing me in class to *explain* code instead of just turning it in.

I would also like to thank the following people for being pretty swell and whatnot.

- Adam Newton Wright for his future contributions on our Nobel Prize-winning discoveries, as one can never have too many gold-plated coasters.
- Kelsey Walker for having optimism so bright it would immediately oversaturate our all-sky camera's sensors.
- Mark Watney for making all my problems seem lame.
- All the angels on Stack Overflow who spend their time answering weirdly specific coding questions that I end up looking at years later.

Abstract

General Abstract

We do not want valuable technology we send out in space to be destroyed by the population of rocks surrounding Earth. Therefore, it is important to know exactly how many rocks are out there and how big they are. Our portable video camera device can detect and then record the rocks burning up in Earth's atmosphere. This project focuses on writing software to see how bright those rocks are based off of the video collected by the device. The brightnesses can be used later to estimate their sizes.

Technical Abstract

When designing new satellites, incorporating damage mitigation techniques is currently difficult due to a lack of understanding about the near-Earth small asteroid population. In an effort to investigate this population, we have constructed a portable all-sky camera to continuously monitor the night sky. It has the capability to detect meteors ablating in Earth's atmosphere and record their brightness as pixel values. To begin to measure the number and size distribution of the meteoroids, this project focuses on writing software to automatically measure a meteor's brightness, and calibrate it to a known astronomic luminosity, which can later be used to estimate its size. When ran on videos from NASA, the program produced similar light curves to theirs, showing a strong proof of concept.

Table of Contents

| | |
|-------------------------------------------------------|-----|
| Acknowledgments | iii |
| Abstract | iv |
| List of Figures | vii |
| 1 Introduction | 1 |
| 2 Background | 3 |
| 2.1 Asteroids and Meteoroids | 3 |
| 2.2 Fireballs and Meteors | 4 |
| 2.3 Near-Earth Objects | 5 |
| 2.4 Detecting Fireballs | 7 |
| 2.5 Analyzing Fireballs | 11 |
| 3 Methods | 15 |
| 3.1 The Photometry Program | 15 |
| 3.2 Recognizing a User's Click | 17 |
| 3.3 Fitting a Contour to the Object | 18 |
| 3.4 Fitting a Gaussian to the Contour | 19 |
| 3.5 Calculating the Magnitude of the Object | 22 |
| 4 Data | 27 |
| 4.1 Iridium Flares | 27 |
| 4.2 Comparison to NASA Data | 29 |
| 4.3 Fireballs Detected with D6 | 34 |

| | |
|---------------------------------|-----------|
| 5 Conclusion | 36 |
| 5.1 Critique | 36 |
| 5.2 Outlook | 37 |
| A Python Packages | 39 |
| B Code | 41 |
| B.1 Data Analysis | 41 |
| B.2 Photometry Script | 42 |
| B.3 GUI Script | 52 |
| Bibliography | 59 |

List of Figures

| | | |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.1 | A visual representation of the different varieties of rock in the space near Earth (Photo courtesy of Dr. Jed Rembold). | 4 |
| 2.2 | The population distribution of near-Earth objects is straightforward: small objects are often much more likely than large objects [RR15]. | 6 |
| 2.3 | Even small objects such as this ball bearing can exert tremendous amounts of force if they are traveling at 50 kilometers per second [ESA17]. | 7 |
| 2.4 | All-sky cameras feature a 360° view of the horizon, providing maximum sky coverage. This is an image from a high resolution color camera [Alc]. | 8 |
| 2.5 | The all-sky camera can see distance z . The area of the Earth it covers is between the points that have the endpoints of z as their zeniths along height h . Note that the height of the atmosphere where ablation occurs is often less than 100 kilometers, while the radius of the Earth is 6,371 kilometers, so the radii are not to scale. | 9 |
| 2.6 | An all-sky camera can cover a circle with a radius of roughly 200 miles. | 9 |
| 2.7 | This network manages to cover a lot of area, but it may not have the best observational quality due to the cameras being centered in cities [Sky]. | 10 |
| 2.8 | This schematic of an all-sky camera leaves out the attached structure to which the bottom cords must connect[Ban12]. | 11 |
| 2.9 | The visual filter, outlined in green, is shifted to the left of the R filter, which is towards the infrared part of the spectrum. The black outline is an example of what a camera's sensitivity may look like [SEM17]. | 13 |

| | | |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.1 | The program runs a series of functions (blue) that return specific information (orange) that is used by the following function. These functions are what make up the entire script. | 16 |
| 3.2 | Within the GUI, A is the selected initial frame, B is the slider to select the initial frame of the event, C is the threshold slider, D is the light curve, E is the data of a selected frame, and F selects that frame. | 16 |
| 3.3 | The first frame of an event. The user clicks on this image in the GUI to select the event. | 17 |
| 3.4 | Each click gives crucial information for later functions: The initial coordinates of the meteor and reference star. | 17 |
| 3.5 | The steps the image is processed with to get a more accurate object position. | 18 |
| 3.6 | A thresholded image, when adjusted properly, allows the program to locate an object easier. | 19 |
| 3.7 | The steps taken to find the Gaussian parameters of the data. . . . | 19 |
| 3.8 | The Gaussian curves in this plot align with the image, so one can visually confirm they are fitting the data. The offset along the tails of the curves are due to the raw data being plotted alongside Gaussian curves made after the background light was subtracted. | 20 |
| 3.9 | The object is located in the center of this slice, and its light fades radially out unevenly from that center. | 21 |
| 3.10 | The steps the function goes through to find the magnitude of the object. | 23 |
| 3.11 | The pixels in red are within the calculated radius for this fireball. | 23 |
| 3.12 | The pixels in yellow are the values being used to find the average background value. The object can be seen inside the yellow ring. . | 24 |
| 3.13 | The pixels in orange are within the object's radius. The yellow pixels are the background ring. The gray area in-between is the buffer. | 24 |
| 3.14 | The program loops over most of the previous functions for each event. | 26 |
| 3.15 | The updating process of the values used as the object's coordinates. | 26 |
| 4.1 | The first Iridium flare captured by D6 at Willamette University can be seen in the lower right quadrant. | 28 |
| 4.2 | While light curves are usually displayed in terms of magnitude, it is important to remember the source of those magnitude values: pixel values. | 28 |

| | | |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 4.3 | The X and Y data slices are plotted alongside the object. The peak of the event flattens out, when one would expect it to curve at the top, similar to the Gaussian curves fitted upon the data. | 29 |
| 4.4 | The light curve NASA attained off the same video is shown in orange in the top right of the graphic [NAS]. | 30 |
| 4.5 | The thresholded image with labels added next to identified objects, next to the Stellarium image it was compared to. | 31 |
| 4.6 | The light curves from the program and from NASA. The NASA light curves are not calibrated, so they are shifted up for easier comparison purposes. | 31 |
| 4.7 | The residuals are randomly distributed except at the very beginning of the event. Ideally, they would be completely randomly distributed. | 32 |
| 4.8 | A violin plot can show the residuals in a histogram-like form. Here, we can see the majority of the residuals are close to zero as that is where the bulk of the violin is. | 32 |
| 4.9 | Light curves collected over multiple events. The general patterns match well in all four, but a few have smaller-scale discrepancies. | 33 |
| 4.10 | The violin plot for all these events have a few outliers, mostly in overestimation. | 34 |
| 4.11 | The interlacing effect makes it appear as if the data is corrupted, as it looks as if there are empty rows in the array. | 35 |
| 4.12 | The light curve of this event is much less smooth than one would expect from a fireball. | 35 |
| 5.1 | There is more air in between someone and an object along the horizon than an object directly above them. | 37 |

1 Introduction

Outer space, while mostly space, is not entirely empty. There are planets, stars, comets, and many other objects, but here we are concerned about meteors. Specifically, we are interested in the smallest meteors. While rocks the size of pebbles may not seem dangerous to those of us protected by Earth's atmosphere, they pose a great threat to equipment and life beyond that atmosphere. We desire to know how many of these objects are in orbit near Earth in order to estimate the necessary level of protection for our structures in space and to better estimate the lifespans of those structures.

Currently, one of the ways meteors can be detected entering our atmosphere is by all-sky cameras detecting the bright streaks they leave as they ablate in the atmosphere. This brightness is what gives them another name: fireballs. All-sky cameras are set up by NASA and other groups[JGD¹¹; TRML⁰⁷]. They are installed on roofs or mounts and hooked up to desktop computers in buildings. It is a big and inflexible setup. This required infrastructure limits the amount of setups that currently exist, which in turn limits the amount of total sky coverage we can get. Our all-sky camera explores a new design: one in which its detection software is housed inside its small, basketball-sized chassis. It currently depends on external power, but low power consumption makes it a strong candidate to run off battery power if needed. We aim to show that our tiny unit (named D6¹) is capable of observing and analyzing fireballs just as reliably as the larger, more established networks.

We are using our all-sky camera to detect meteors, utilizing photometry to calculate the meteors' magnitudes, and then extrapolating their masses from those magnitudes. There have been many other studies by larger all-sky networks to create a model for the population distribution. We have no reason to expect our data to deviate greatly from this trend. In fact, we are hoping to test the effectiveness of our all-sky camera setup by comparing its findings to the established model. Also, while the general trend is well known, there is no guarantee that it

¹D6 is named after a droid in the Star Wars universe similar to R2-D2, but is green and owned by Rebellion hero Wedge Antilles.

is as precise as it could be. We are curious about any possible small discrepancies within the model regarding the smaller size meteoroids, and believe that if any discrepancies are there, they would only become apparent if data was being collected much more frequently than the current rate.

Chapter 2 details the information needed to understand what fireballs are and why they are important. The size of a meteor is determined through a long chain of physical relations that begin at its apparent magnitude. The photometric analysis done to find that apparent magnitude is explained in detail in Chapter 3. The actual results are then presented in Chapter 4.

2 Background

With respect to the Sun, our planet is moving through space at 30 kilometers per second. Many other objects orbit the sun, and their orbits can overlap or nearly overlap Earth's. The vast majority of these objects are small and are difficult to detect. These objects are known as near-Earth objects. Near-Earth objects consist of many similar rocks, but they have important differences between them. Regardless, they are hazards of the solar system, so we use systems such as all-sky cameras to detect them and gather data about their population distribution.

2.1 Asteroids and Meteoroids

There are five terms that are often incorrectly used interchangeably to describe rocks from space. They are the following: asteroid, meteoroid, meteor, meteorite and fireball. They are visually represented in Figure 2.1. Compositionally, asteroids and meteoroids are the same. They are composed of rock or metal and travel through space outside Earth's atmosphere. They are delineated by their size. In order to be defined as a meteoroid, the piece of rock should be at least $100 \mu\text{m}$ ¹[Ste96]. The accepted upper boundary on what constitutes a meteoroid but not an asteroid is around 10 meters. Asteroids are much larger, such as the asteroid that caused the Chicxulub crater in the Yucatan peninsula [Bot07]. It should be noted that a comet does not belong with these terms as only a small percentage of a comet's composition is rock: it is a mass of ice and dust.

In terms of their origins, meteoroids are often fragments of asteroids that are separated by some sort of collision in space, or are small pieces of rock and dust that are left behind by comets. Near-Earth asteroids are most likely objects expelled from the main asteroid belt between Mars and Jupiter due to Yarkovsky thermal forces or secular resonances [Bot07]. The Yarkovsky thermal force is a net force that occurs from the heating up of one side of an asteroid or meteoroid

¹Anything smaller than this is nothing more than dust, which makes up the interplanetary dust cloud.

from the Sun. The hotter side dissipates more energy while it cools than the cold side, and thus that departing energy results in a recoil force moving the asteroid in the direction opposite the hotter side [BVRN06]. Secular resonance is when an asteroid syncs its precession to a nearby planet. This disturbs the orbit of the asteroid, and causes it to slowly change its orbital eccentricity as a result [MM95].

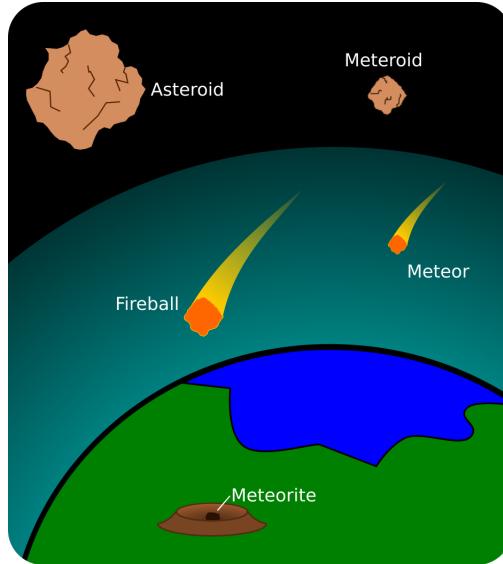


Figure 2.1: A visual representation of the different varieties of rock in the space near Earth (Photo courtesy of Dr. Jed Rembold).

2.2 Fireballs and Meteors

Asteroids and meteoroids are by definition only found outside the atmosphere of the planet. They become meteors only when they enter the atmosphere. Some literature even rechristens their status from near-Earth objects to inside-Earth objects, or IEOs [Bot07]. Fireballs are especially bright meteors, and are often chosen to be studied due to their comparatively easy detection. Technically, fireballs are only considered such if they are brighter than Venus, with a magnitude of around -4, but the colloquial use is much less stringent [Har08].

Most of the time meteors are completely destroyed as they travel through the atmosphere. They are destroyed through ablation due to interactions with molecules in the atmosphere. As the meteor hits the molecules in the atmosphere, ionization occurs. The point in the atmosphere at which light is emitted varies based on the velocity of the object. Slower objects need to be in a denser part of the atmosphere before ablation can occur. The height at which this happens is most often between 70 and 110 kilometers above sea level [HGB96]. During this

process the meteor loses mass and energy in the form of light. The percentage of energy converted to light is known as the luminous efficiency and is an important term in predicting the mass of a meteor from its luminosity. If there is still mass remaining by the time it comes into contact with the Earth, it cools and becomes a meteorite. More often than not, however, meteors are vaporized tens of kilometers above sea level [HGB96].

Meteors tend to appear during two types of events. The first event is a meteor shower and can be reliably predicted. This is due to Earth going through parts of space where known debris is located. The debris is trails left behind by comets. The majority of these comet trails are due to water vapor drag. As a comet moves around the sun, its ice evaporates, freeing the small pieces of rock that were embedded inside it [Whi51]. A meteor shower can also be caused by a large amount of debris left behind when a comet is fragmented in space [Jen06]. Many meteor showers are well charted and known at this point. As of this writing there are 112 established meteor showers, with the potential of hundreds more to be discovered [R R17]. Besides a meteor shower, the other event is a single isolated event, called a sporadic event. A sporadic event may have originally been part of a meteor shower or an asteroid belt before getting set off course due to extraneous forces.

2.3 Near-Earth Objects

While there are differences between the types of near-Earth objects, they all share one thing in common: they pose a hazard to any sort of human structure sent out into space. Having more accurate and complete data on the population of these objects will give humanity a better chance to adequately defend these structures and shelters as well as more accurately estimate their lifespans. As space exploration develops, this will become more and more relevant, with potential landing spots for humans on the Moon and on Mars not having the luxury of the protective atmosphere of Earth. This can be seen just by looking up at the night sky; the Moon is pockmarked with craters. This is not just exclusive to the moon, as craters can be seen on any rocky space object that does not have a thick atmosphere. These craters are the most obvious evidence of meteor strikes. The Moon also provides another strong example of the power of these strikes, as when a meteoroid hits the lunar surface, enough energy is released as to be visible from Earth [RR15]. Without the protective atmosphere, near-Earth objects could potentially wreak havoc on any space structures. For example, the European Space Agency communication satellite Olympus was permanently decommissioned due to damage sustained during the Perseid meteor shower of 1993. The majority

of international and national organizations² concerned with planetary protection have all deemed large near-Earth objects to be credible threats to Earth and to any missions out of its atmosphere [Bot07].

Observational data from many different studies has resulted in a model for the population distribution of these objects. Specifically, there is a well-known linear relationship between the mass of an asteroid and the number that exist if plotted along log-log axes [RR15]. This is shown in Figure 2.2.

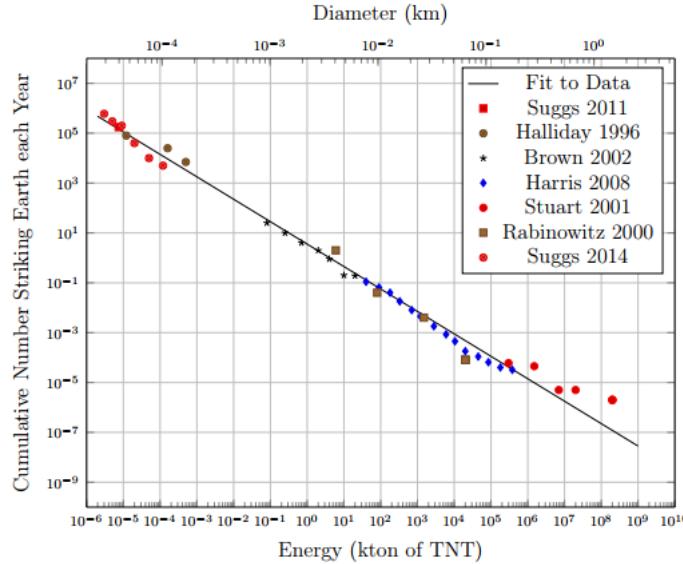


Figure 2.2: The population distribution of near-Earth objects is straightforward: small objects are often much more likely than large objects [RR15].

Initially this model seems reassuring. The larger objects, which would have the most potential to cause damage, are much less common than the smaller, less energetic objects. The smaller objects would have less energy as

$$\text{Kinetic Energy} = \frac{mv^2}{2} \quad (2.1)$$

where m is equal to the mass and v is equal to the velocity of the object. However, these small objects still pose a large threat to structures due to their extremely fast velocities. A one-millimeter meteoroid has similar destructive capability as a 22-caliber bullet, while a one centimeter meteoroid can be as powerful as a cannonball. This is because velocity is the dominant term in Equation 2.1 and meteoroid speeds can range from 11 to 70 kilometers per second [Har08]. Figure 2.3 shows the damage that a pebble-sized object can do to a thick slab of metal, and satellites without armor are much more fragile than that.

²These include, but are not limited to, the United Nations, the United States Congress, the European Council, the UK Parliament, the IAU, OECD, NASA, and ESA [Bot07].



Figure 2.3: Even small objects such as this ball bearing can exert tremendous amounts of force if they are traveling at 50 kilometers per second [ESA17].

It should be noted that while this model appears consistent, it is still an observational model and thus it is not necessarily perfect. With such a high population of smaller-sized objects, any variance could greatly change the likelihood of accurately accounting for potential damage. For instance, a satellite can only take so many impacts with meteoroids before becoming disabled. Even if there are only slightly more meteoroids than currently predicted, the lifespan of that satellite would be shortened, jeopardizing missions.

2.4 Detecting Fireballs

There are many current projects aimed at collecting optical data about meteors [JGD⁺11; TRML⁺07; HGB96]. Most make use of all-sky cameras. All-sky cameras are CCD cameras that are often utilized as video capture devices, recording either 25 or 30 frames per second depending on its video signal [MG05]. An all-sky camera is a camera that provides a view of up to 180° of the sky above, producing a circular image, as seen in Figure 2.4. This allows a clear view of the sky as a whole, allowing for easy identification of constellations. By locating constellations, stars can be identified and objects can have their relative location recorded.

In reality, this view is not quite 180° , but more often around 140° due to the fact that lenses wide enough to take in 180° end up just taking in the edges of the all-sky cameras chassis instead. Our own camera is only able to see 140° of the sky. Figure 2.5 shows how much of the sky is covered. The amount of Earth being covered is defined by taking the edges of the all-sky camera view and treating those as zeniths. A zenith is the point in the sky that is directly above a certain point on Earth. Those points on Earth are the edges of how much of the Earth it covers. Knowing how much of the Earth is covered is useful because those

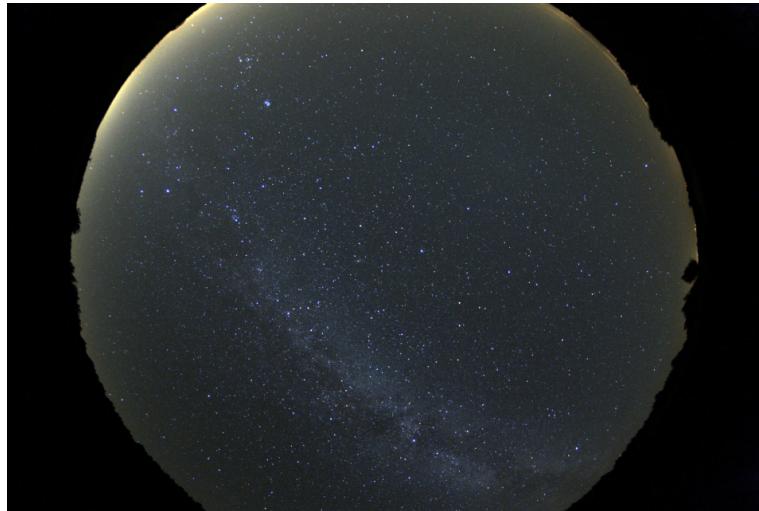


Figure 2.4: All-sky cameras feature a 360° view of the horizon, providing maximum sky coverage. This is an image from a high resolution color camera [Alc].

zeniths provide the points where another camera can be placed to overlap one half of the original camera's view of the sky. Overlapping is useful because multiple cameras seeing the same event allows the triangulation of the object's position and velocity. The amount of sky coverage can be written, using trigonometry, as

$$\text{Sky Coverage} = \Omega(h + r)^2 \quad (2.2)$$

where Ω is the steradian, and $h + r$ is the distance from the center of the Earth to the edge of the area of sky coverage.

Using an average height h of 75 kilometers, the area of the sky that is covered by an all-sky camera such as ours is around 119,000 square kilometers. This is equal to 118,000 square kilometers of land coverage. This is only 0.023 percent of the Earth that is covered, so there is a need for more all-sky cameras to ensure better coverage. Our all-sky camera has been in two locations, Salem and Baker City, Oregon. 2.6 shows how much land can be covered in those two spots. Even for two locations in the same state, there is no overlap.

All-sky cameras are currently detecting fireballs in many places around the world. One notable example is NASA's Camera for All-Sky Meteor Surveillance (CAMS) Network. They have cameras located throughout many parts of the United States, forming a strong cohesive network. The CAMS network has been successful in correctly detecting all known meteor showers³ during the month of November in 2011[JGD⁺¹¹].

³The meteor showers were the theta Aurigids, chi Taurids, omicron Eridanids, and the supposed iota November Aurigids. The latter was in fact shown to be merely an overlap between the theta Aurigids and chi Taurids with CAMS network data.

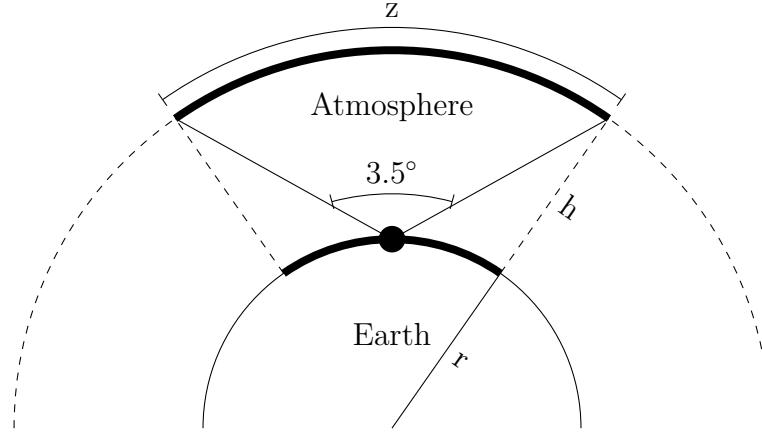


Figure 2.5: The all-sky camera can see distance z . The area of the Earth it covers is between the points that have the endpoints of z as their zeniths along height h . Note that the height of the atmosphere where ablation occurs is often less than 100 kilometers, while the radius of the Earth is 6,371 kilometers, so the radii are not to scale.

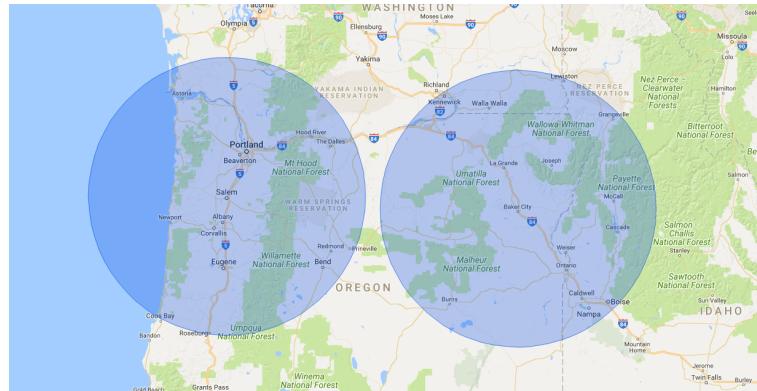


Figure 2.6: An all-sky camera can cover a circle with a radius of roughly 200 miles.

NASA is not the only one to have such a network, with other organizations such as the Spanish Meteor Network (SPMN) also possessing well established systems of their own. They were able to successfully confirm expected meteor showers with the use of their high-resolution, all-sky cameras.⁴ They were even able to find the nu Aurigids, that while previously identified, were not expected to be seen [TRML⁰⁷]. These organizations are able to collect large amounts of data with all-sky camera networks compared to previous endeavors but they do not have enough cameras to come even close to covering the entire sky. Figure 2.7

⁴The meteor showers were the Orionids, the Taurid stream related to comet 2P/Encke, and the delta Aurigids.

shows the Sky Sentinel Camera Network and their coverage in the United States. The network currently operates a network of around 65 cameras and hope to have over 100 in the future [Ban12].

The current model is to have these cameras connected to large structures or buildings with desktop computers where they can access the constant power and internet access that is needed for the detection and analysis. The necessary infrastructure that is currently needed requires these networks to be built in more urban areas, where light and air pollution become more problematic. Therefore this model also severely limits not only the quantity of skies covered, but also the quality.

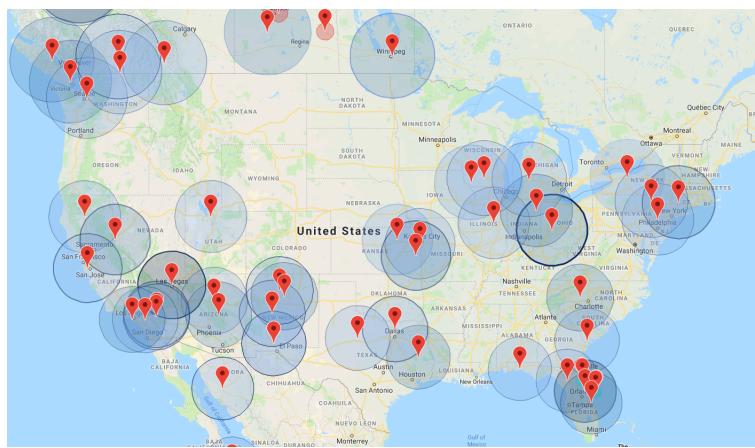


Figure 2.7: This network manages to cover a lot of area, but it may not have the best observational quality due to the cameras being centered in cities [Sky].

All-sky cameras themselves are not inherently complex. They are small and can be built relatively cheap, with builds being found online from Sky at Night Magazine and New Mexico State University, among others [Ban12]. Figure 2.8 shows the diminutive size of a camera used by the Sky Sentinel network, but also shows the power and video signal cords that have to connect to an external desktop for analysis.

Having a small, portable system has many potential benefits. Not only does a portable system increase ease of use and decrease equipment cost, it also vastly improves flexibility. For example, if nearby blooming trees block some view of the sky during the spring, a portable system could just be moved, while a permanent system would require the removal of the trees or the acceptance of a less than optimal observational status.

Software accompanies all-sky camera systems to perform meteor detections. The software saves the user from having to watch hours of video looking for events that may just be a few seconds long. Detection systems look for moving patches of light, and thus can produce numerous false positives from other environmental

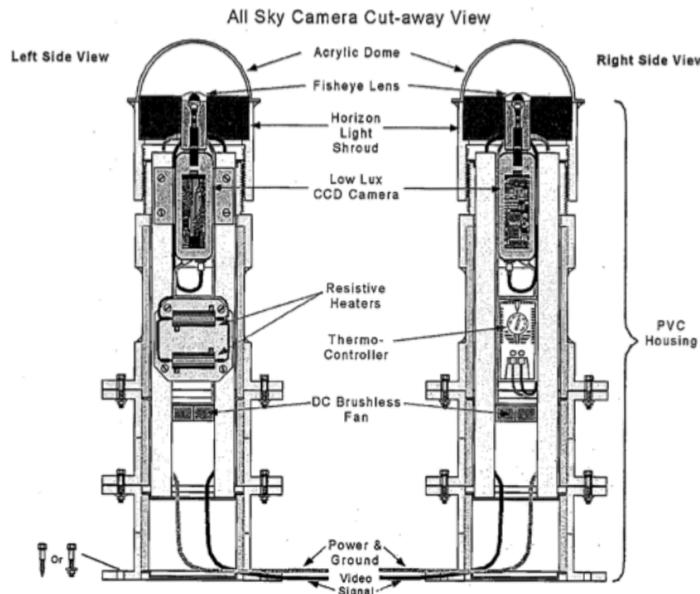


Figure 2.8: This schematic of an all-sky camera leaves out the attached structure to which the bottom cords must connect[Ban12].

factors. These include light being reflected off of moving clouds and planes flying through the field of vision [Har08]. Fortunately, these false positives can mostly be eliminated by visual inspection. The exact setup depends on the specific system, but meteor detection is either constantly processed by a computer checking the frames as they arrive or the video is stored as a whole to be run through a detection program at a later date [MG05]. The software is somewhat bulky as a result. For example, METREC is a meteor detection software that is used by networks such as the Polish fireball network. It requires a desktop computer to operate[MG05].

2.5 Analyzing Fireballs

An all-sky camera can acquire many pieces of useful information about a meteor. That being said, there are parameters a single all-sky camera cannot extract that a full network can, such as velocity and height. If there is a system of multiple cameras detecting the same meteor, the orbit can be extrapolated as well [TRMW⁺09]. The Canadian fireball network detected 259 fireballs in 1996, and was able to get values for height, velocity, magnitude and mass for every fireball [HGB96]. A single all-sky camera is only able to get magnitude, and would have to extract mass from that. For a full fireball network, having velocity

means it can find the mass with the relationship

$$\frac{m_d}{A} = -\frac{\rho_a v^2}{2\dot{v}}, \quad (2.3)$$

where m_d is the mass at a certain point in the flight, A is the cross sectional area at that same point in flight, ρ_a is the atmospheric density, and v is velocity [HGB96].

Not only does the velocity help determine mass in this situation, it also can be used to work backwards to find an estimate of the velocity before the affects of drag began slowing it down. This means that all-sky cameras can be used to gather data on the potential velocities of meteor showers in open space. The Spanish Meteor Network (SPMN) used velocity data to extrapolate such pre-atmosphere velocities with their five station setup in 2006 [TRML⁺⁰⁷].

Ultimately, all-sky cameras are most useful for measuring the photometric qualities of objects in the sky. They can detect fireballs and then provide the needed data to determine the fireballs' magnitudes, which is how bright they appear to the camera. This can be done with just a single all-sky camera.

It should be noted that there are differing techniques for performing photometry. Different cameras are more sensitive to different wavelengths of light, and that can make comparing results from different cameras challenging. One solution to this is to apply a filter. A filter isolates light along a specific wavelength of the electromagnetic spectrum, as shown in Figure 2.9. For example, a visual filter is one that focuses on visible light, being centered on the wavelength for green light. The most commonly used values for star magnitudes are values determined after applying a visual spectrum filter. If a camera is more sensitive towards the infrared spectrum, an R filter might better fit its spectrum, and can be applied instead [SMCS14]. It is possible to compare magnitude values with two different filters, but the process is somewhat convoluted and best to be avoided.

In some cases, it is useful to not apply a filter at all. While this can make it difficult to calibrate the camera to other known values, this guarantees that all light is being detected. This is crucial in highly sensitive detection situations where it would be ill-advised to sacrifice any of the small amount of potential data [RR15]. Even if no filter is applied, knowing the different bands allows the comparison of data to similar observations. For example, if the unfiltered camera sensitivity closely approximates the R band, R filter magnitudes are comparable.

The luminosity can be used to find the mass, but only by using approximations for other values such as density, which can be estimated due to the structural analysis of meteorite collections. As luminosity is the only needed data point, a single all-sky camera is viable for measuring the population distribution.

But how does one get from intensity to luminosity? The relationship between the two is

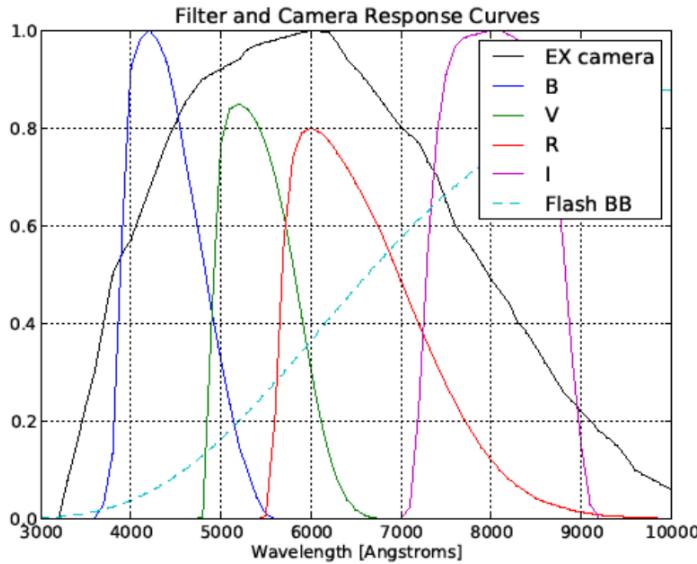


Figure 2.9: The visual filter, outlined in green, is shifted to the left of the R filter, which is towards the infrared part of the spectrum. The black outline is an example of what a camera's sensitivity may look like [SEM17].

$$L = (SA)I, \quad (2.4)$$

where L is luminosity, I is intensity, and SA is the surface area over which the light has propagated. In order to find the luminosity from intensity, we need to assume that the object radiates energy equally in all directions, forming a sphere. This assumption is not too far off from the actual appearance of most meteors. Making this assumption, Equation 2.4 becomes

$$L_{obs} = 4\pi r^2 I. \quad (2.5)$$

Now that the intensity is converted to luminosity, that luminosity can then be used to find its total kinetic energy. The relationship between the two is

$$L = \tau T, \quad (2.6)$$

where L is again luminosity, T is kinetic energy per second, and τ is the luminous efficiency. Again, the luminous efficiency is simply the proportion of a fireball's energy that is dissipated as light. Once the kinetic energy per second is known, we can relate it to mass through the relation

$$T = \frac{v^2}{2} \frac{dm}{dt}, \quad (2.7)$$

where v is velocity, m is mass, and t is time. Again, with only one all-sky camera assumptions about the velocity have to be made, but as velocities of meteors vary at most by a factor of 2, this assumption does not create problems along the log-log graph of Figure 2.2. The error bars created by this assumption could be easily reduced by having multiple all-sky cameras detect the event. Notice that while the mass of an object is usually treated as constant when calculating kinetic energy, since the entirety of the object's mass is burning up, we can integrate over the entire event to find that original mass. This integral can be written as

$$m = \int \frac{2L}{\tau v^2} dt. \quad (2.8)$$

This integration is why the entire light curve of a meteor event needs to be collected. The methods for doing so is described in Chapter 3.

3 Methods

The size of a meteor are determined through a long chain of physical relations that begin with its apparent magnitude. So, the first thing to do is find the magnitude of the fireball when D6 detects it. We have written a script where we can find the magnitude of the fireball as long as we know the apparent magnitude of another celestial object in the sky. This is done by automatically finding the center of the meteor the user selected on the image, and then automatically detecting the edges of the object through the creation of a fitting centroid. A Gaussian curve is then fitted to its light curve to provide an estimate of the fireball's radius. All the pixels within that radius is then summed over. This summation of pixels gives us the raw magnitude for our specific camera. The general outline can be seen in Figure 3.1. Each of the steps are explained in more detail in the following sections.

3.1 The Photometry Program

Once an event is detected by D6, it can then be run through a script that will analyze the frames and output the desired photometric information. The script is written in Python 3, and the user can run it through the use of the accompanying graphic user interface. The interface can be seen in Figure 3.2. A user simply runs the script while directing it to the location of the video they would like to analyze. The program runs through the video a single frame at a time, and loops through its functions until completing analysis on all frames in the video.

The video processing is done through using the video read functionality of OpenCV. The video frames are always converted to grayscale at the beginning of the loop, so there is only one channel of pixel values instead of three that would occur with color video, which correspond to the red, green, and blue channels.

Upon running the script, the user will first see the first frame of the video. An example of a frame that a user could see is seen in Figure 3.3. This is where the user will be required to make a selection on the screen identifying where the object and reference stars are located. The user simply left clicks on the desired

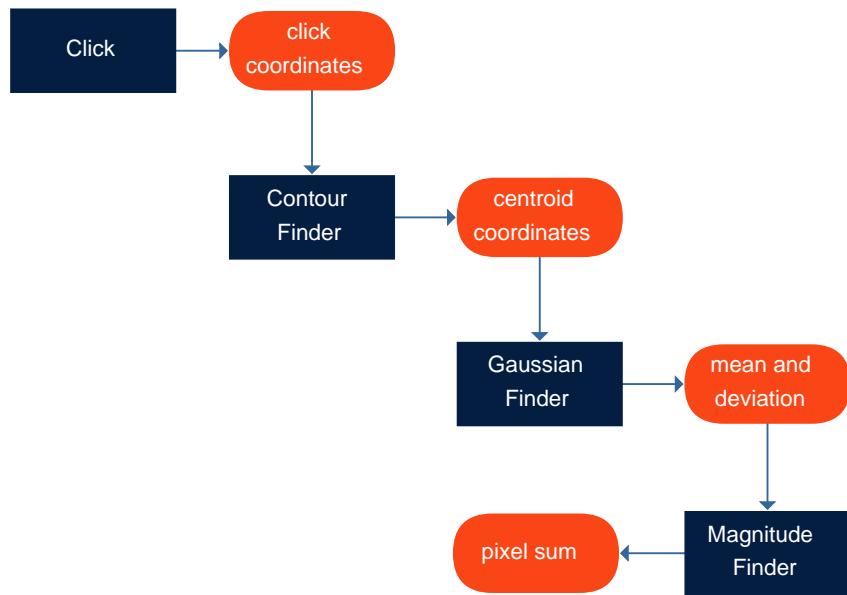


Figure 3.1: The program runs a series of functions (blue) that return specific information (orange) that is used by the following function. These functions are what make up the entire script.

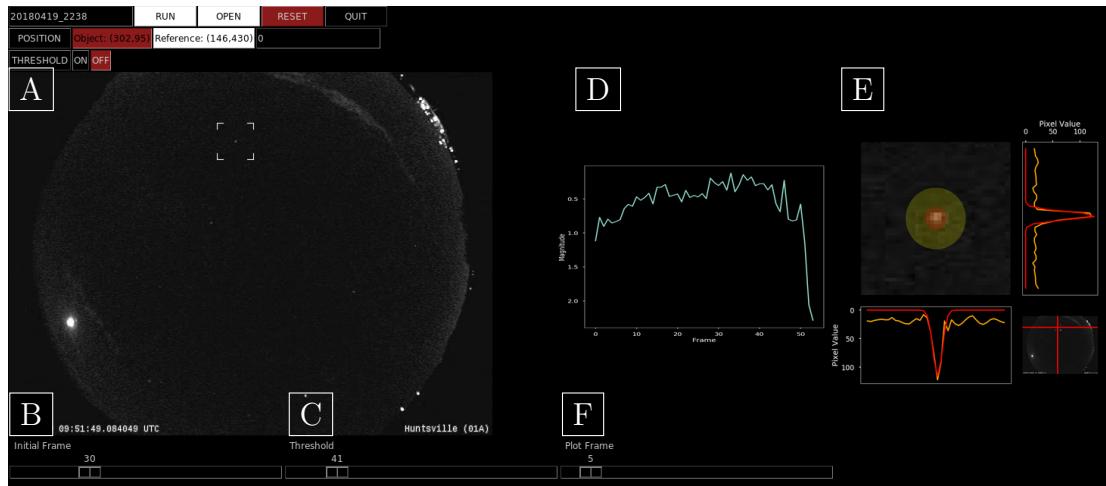


Figure 3.2: Within the GUI, A is the selected initial frame, B is the slider to select the initial frame of the event, C is the threshold slider, D is the light curve, E is the data of a selected frame, and F selects that frame.

object, and right clicks on a reference star of known magnitude. The user uses a slider to adjust the threshold level until both objects are clearly separated from the background. The user's clicks initialize the script.



Figure 3.3: The first frame of an event. The user clicks on this image in the GUI to select the event.

3.2 Recognizing a User's Click

Why does the user need to click on the objects? The program needs a general idea of where the object in question is on the frame. It can follow the moving object after that as long as it has a starting point. This is outlined in Figure 3.4.



Figure 3.4: Each click gives crucial information for later functions: The initial coordinates of the meteor and reference star.

Using the `OpenCV` computer vision python package, the coordinates of the user's clicks can be extracted and used in the script. The user's left click records the corresponding X and Y coordinates as a tuple identified as the location of the object. The user's right click records the corresponding tuple as the location of the reference star. The user can click multiple times, with each click overwriting the previous one until the user is satisfied with their click accuracy. After both

objects have been selected, the program's Run button becomes selectable. The user clicks the button to run the remainder of the script.

3.3 Fitting a Contour to the Object

The location of the object is now set as the exact pixel the user clicked on. The user may have provided a solid estimate of where the true center is with their click, but it is most likely not actually the true center. The estimate allows the program to run its algorithm to find a more accurate location of the object in the nearby vicinity of the click. The aforementioned algorithm's process is outlined in Figure 3.5. This more accurate object location will be necessary when the program tries to fit Gaussian curves to the data, which will be needed to estimate the radius of the object.

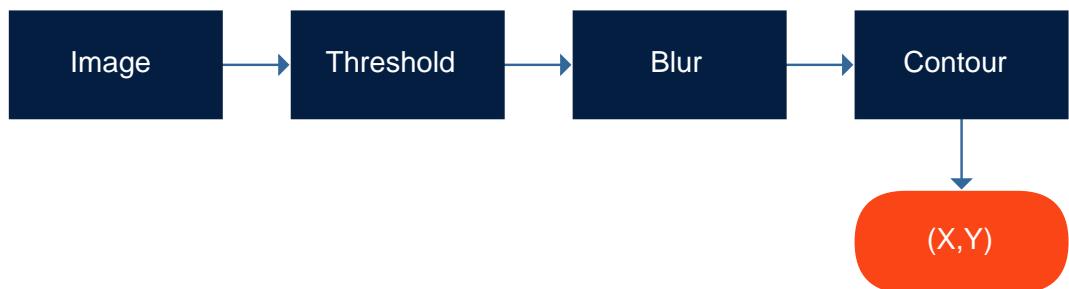


Figure 3.5: The steps the image is processed with to get a more accurate object position.

The script takes the X and Y coordinates of where the user thinks the object is and isolates that part of the frame. The image is then blurred using an OpenCV command that blurs the edges of the pixels using a Gaussian equation to fade their light. This is done as an array of pixel values is discrete, and not ideal to model a continuous equation, such as a Gaussian, off of. The image is then thresholded at a certain percentage. Thresholding essentially divides all pixels into a group lighter than a certain percentage and a group darker than that percentage. The darker pixels are all turned black, and the lighter pixels are all turned white. This, combined with the blurring, turns the object into a white round object. An example of this process can be seen in Figure 3.6. This process also has the benefit of making it easier for the user to locate the object. It is especially useful for finding the reference star, which is often much dimmer than the meteor.

Another OpenCV command called `findContours` is implemented to find the center of that ellipse. Its algorithm is exactly like how one would find the center of mass of an object, but with the intensity of the pixel being the “mass” in



(a) The image before being thresholded. (b) The image after being thresholded.

Figure 3.6: A thresholded image, when adjusted properly, allows the program to locate an object easier.

the calculations. At this point, the program now has a much more precise idea of where the center is. With the object's coordinates updated, the thresholded frame is discarded, and the following analysis is continued with the undoctored data.

3.4 Fitting a Gaussian to the Contour

Now that there is an accurate object location, we can fit a Gaussian curve to the data in both the X and Y dimensions. We want to do this because having a Gaussian curve gives us a known standard deviation, and we can then calculate the radius of the event using that standard deviation. This process is outlined in Figure 3.7.

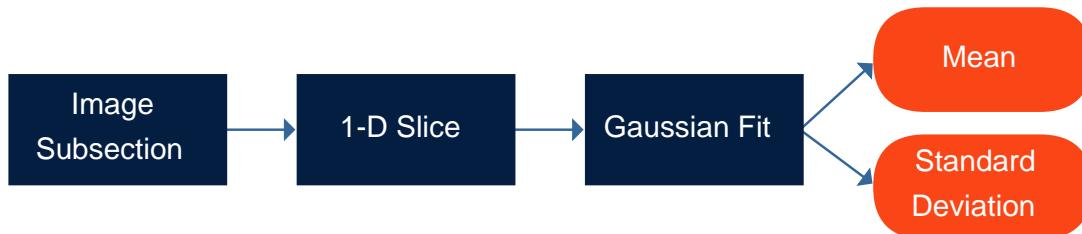


Figure 3.7: The steps taken to find the Gaussian parameters of the data.

The formula for a Gaussian curve is

$$ae^{-(x-x_0)^2/(2\sigma^2)}, \quad (3.1)$$

where a is the amplitude, x is the point along the curve, x_0 is the center of the curve, and σ is the standard deviation. A package is used from the Python library

called **SciPy**¹. A Gaussian fitting will output a mean and standard deviation, but first the **SciPy** function needs a strong estimate of the mean to attempt to fit the data. This is why the center of the object was calculated using the contour method previously discussed. In our program, we calculate two one-dimensional Gaussian curves across that center. The function fits the Gaussian curves to 20-pixel slices centered at the point in the X and Y directions. The Gaussian curve also returns its mean, and the mean of the X slice and Y slice is updated to represent the objects location once again, which is used to fine-tune the location of the event. The clicking, contouring, and Gaussian fitting functions can be thought of as a sequence of steps to acquire the most accurate center, along with the acquisition of the standard deviation data mentioned. The curves can be plotted and saved as PNGs. The Gaussian curves of one such frame can be seen in Figure 3.8.

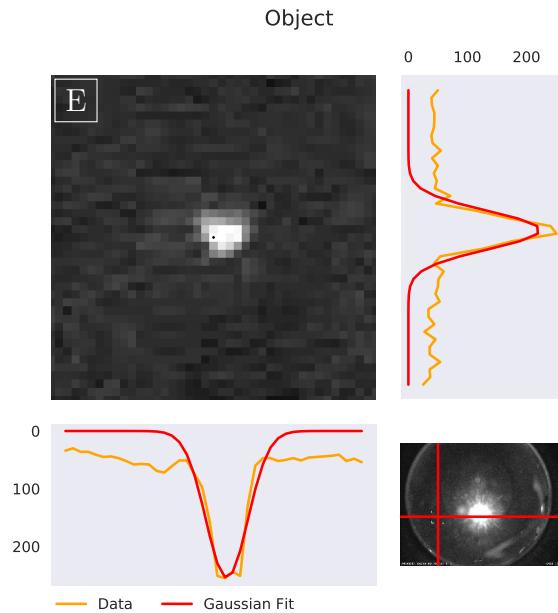


Figure 3.8: The Gaussian curves in this plot align with the image, so one can visually confirm they are fitting the data. The offset along the tails of the curves are due to the raw data being plotted alongside Gaussian curves made after the background light was subtracted.

Occasionally, an anomaly or poor data will make the Gaussian function unable to actually fit the data to a Gaussian curve. In this case, an exception is called in the code to just use the estimates provided as the true outputs of the Gaussian function instead of the error message. By using the estimates, the sequence of

¹The author prefers the package to be pronounced “skip-ee” when discussing any matter involving this paper.

functions can continue as-is without any additional manipulation. The frame is skipped in the creation of the final light curve. This is done to ensure the program can finish to completion, and not end in the middle. If this was not implemented, the program would break before processing the command to create the light curve. Later on, it is possible to view the data to ensure the Gaussian curves aligned well with the pixel values, as shown in Figure 3.2.

A Gaussian curve is to be expected from something such as a point light source as it dims out radially. An object will not have a definite edge: it will fade away into the background, as seen in Figure 3.9. The Gaussian function has the benefit that its standard deviations are directly proportional to certain percentages of the data fitted to the function. This is commonly known as the 68-95-99.7 rule: one standard deviation covers 68% of the data, two standard deviations covers 95% of the data, and three standard deviations covers 99.7% of the data. After that, the diminishing returns are not enough to overcome the extra noise in our data.

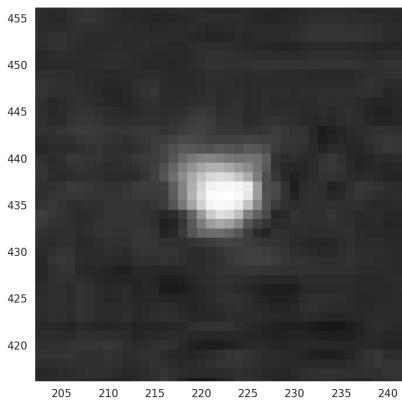


Figure 3.9: The object is located in the center of this slice, and its light fades radially out unevenly from that center.

There are few more details in the calculation of the radius from the standard deviations, however. The X and Y radii are defined by multiplying their respective Gaussian curve standard deviations by three, and then rounding up to the nearest integer. While the standard deviations themselves may be decimals, the image's pixels consists of only integer values, so any other number would not be compatible. In other words, one can not sum over a fraction of a pixel; either the entire pixel must be used or none of it is. The radius of the circle is then defined to be whichever of these two radii happen to be the largest. The pixels within this radius will be summed over in the next section.

Why do we sum over all the pixel values inside the radius instead of just integrating over the Gaussian fit? Figure 3.9 also provides a strong piece of visual evidence why someone wanting to just integrate over a two-dimensional Gaussian

using the X and Y Gaussian slices would be oversimplifying the nuances in the data. First off, a Gaussian function is by definition a continuous function; that is one of the reasons it is so nice for finding the radius, as all of its values are usable. However, the data itself consists of pixels, a discrete form of data. This is why the program runs the radius up to the nearest integer; one cannot sum over a fraction of a pixel. This discreteness in the data is inherently different than a continuous model, and if the sum was found off that, it would be making too many assumptions about what the data *could* be instead of what it actually *is*².

All of this reasoning is still making one critical assumption of the data: that it is perfectly radially symmetrical. With the actual photometric data, we can clearly see there are some fluctuations in how wide the radius is at different points. In Figure 3.9, the object's appearance is stretched in the upper-left direction and in the upper half in general. This is why it is critical to remember that the Gaussian is merely an approximation used to automate the calculation of the radius. It is *not* perfect, and does not represent the data particularly well as a whole. What it does do well, however, is give a solid representation of where the majority of the pixels are.

3.5 Calculating the Magnitude of the Object

Now all of the needed information is gathered to find the magnitude of the object at that frame. With the parameters from the Gaussian function, we know where the object is centered and, by defining its radius to be three standard deviations, we know the radius of the object. After subtracting background light, we then can sum over all the pixels within that radius to find the amount of light, or the magnitude, that our camera sees from the object. Doing this every frame gives us the light curve of the event over time. A diagram describing this process can be seen in Figure 3.10.

The radius can give us the lengths along the axis, but not the pixels of the entire circle we are searching over. The program takes a 10×10 search area around the center point, and checks all the points to see if they lie inside the given radius using the distance formula. If a point is within the radius, it is appended to a list to be used later. An example of this can be seen in Figure 3.11.

We need to remove the background light from the calculation so we can sum over the pixel values attributed to only the object's light, and not from any other source. If the background light is not subtracted the values of the pixels would be artificially elevated due to the existence of that inherent background light. To do this, we need to create a second radius around the circle that can be used to

²And while some assumptions have to be made in this photometry analysis, for that reason we cannot really afford to make any superfluous assumptions.

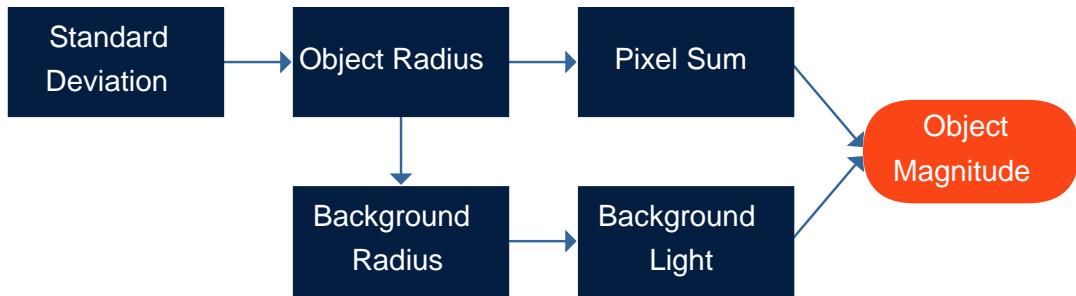


Figure 3.10: The steps the function goes through to find the magnitude of the object.

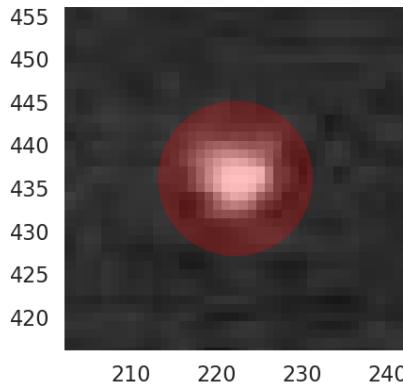


Figure 3.11: The pixels in red are within the calculated radius for this fireball.

determine the average value of the background light. The background light can be somewhat noisy, so that is why we take an average of a group of background pixels. The pixels in question are chosen by finding pixels within a radius of the object's radius plus 10 pixels, excluding the pixels inside the object's radius. This creates a ring around the object's radius, as shown in Figure 3.12. In theory, if the Gaussian-based radius is too large, the background light subtraction will mitigate that overestimation.

One problem that occasionally happens is the background search radius will go beyond the actual size of the image. This problem occurs when an object gets close to the sides of the image. In order to prevent this from crashing the program, a loop goes through the pixel indices in the background list and checks to make sure they are not greater than the dimensions of the image. If any are, they are ignored.

There is also a one pixel buffer between the two areas for extra wiggle room. This is important due to the conversion to integers when finding the two radii.

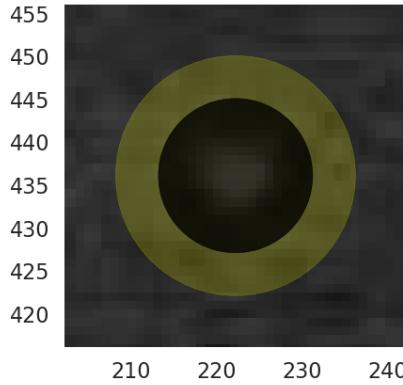


Figure 3.12: The pixels in yellow are the values being used to find the average background value. The object can be seen inside the yellow ring.

The radii are not perfect circles, and as the distance may also be in the middle of a pixel, you can not just split it. Both of the radii calculations round up, and take that whole pixel, which could create a pixel on the edge of the background radius and the object radius being used in both summations if there was not a buffer zone. This is easily seen when both the object's radius and the background ring is displayed on the same picture, such as in Figure 3.13.

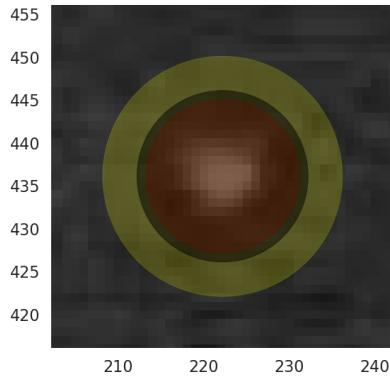


Figure 3.13: The pixels in orange are within the object's radius. The yellow pixels are the background ring. The gray area in-between is the buffer.

The program then sums all the pixel values in the list of values that were within the inner radius. This is done through a for-loop that adds the value onto itself with every iteration through the list, while subtracting the average background magnitude from each individual point. This is the raw measurement of light from our specific camera.

Cameras have different sensitivities, so there is an offset that needs to be accounted for to have our specific camera be able to calibrate to the standard

units of magnitude. This can be appended to the general calculation of magnitude, resulting in

$$M_I = -2.5 \log_{10} \left(\sum \text{pixels} \right) + \text{offset} \quad (3.2)$$

where M_I is now the *instrumental* magnitude. This relationship was elaborated on in the Background section. The offset can be calculated as

$$\text{offset} = M_I - M_C \quad (3.3)$$

where M_I and M_C are the instrumental magnitudes and catalog magnitudes of the same object.

This is why a reference star is needed. The object in question, the fireball, does not have a catalog magnitude, but the reference star does. This calculates the offset for the camera, which then can be applied to Equation 3.2 for the fireball. This offset is calculated as an average over the entire event. The average is calculated due to the small amount of fluctuation each frame may have in their offsets due to variables such as atmospheric distortion or haze.

The program runs the previously mentioned functions for every frame in the video, and loops through this process until the video is completed. This is summarized in Figure 3.14. In order to successfully loop through the frames, there needs to be a way for the program to jump from the center of the object in one frame to the center in the following frame. The process of calculating a more precise center through each function allows the program to adjust the previous frame's center to the next frame's center without any difficulty. This is because the amount of pixels the center of the object appears to travel in each frame is usually no farther a distance than the average user's click is from the actual event for the first frame. This process is shown in Figure 3.15.

PNGs of each frame's Gaussian fits along with the visualization of the radii are optional through the loop. If enabled, the result is exactly like Figure 3.8. When this option is on, the program may take up to 30 seconds to run, as it is memory intensive to save hundreds of PNGs. If it is disabled, the program finishes within a second. When finished, the program displays the light curve inside the GUI, and saves it to the selected folder along with the data as CSV files.

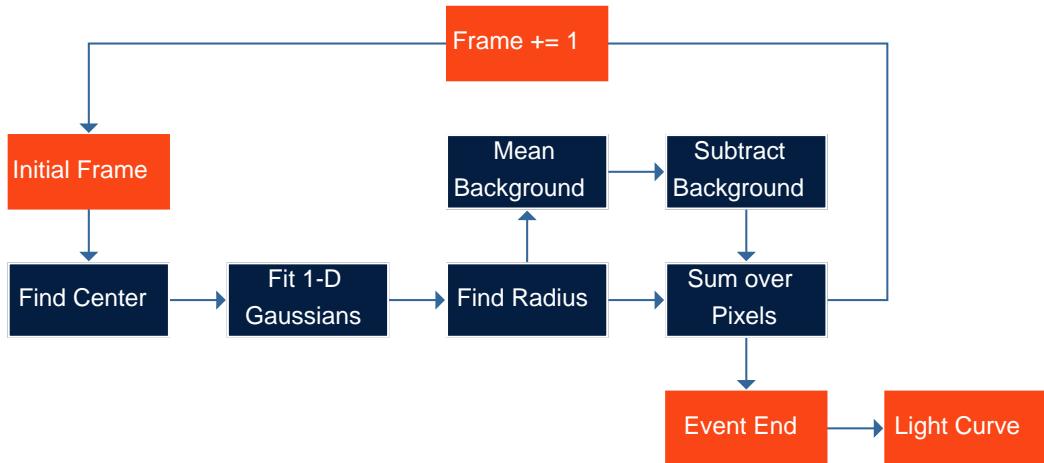


Figure 3.14: The program loops over most of the previous functions for each event.

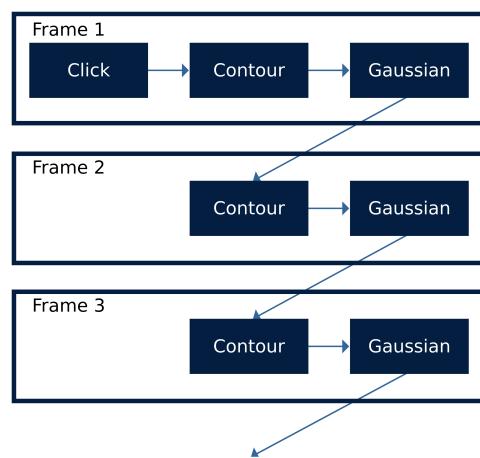


Figure 3.15: The updating process of the values used as the object's coordinates.

4 Data

There are three types of data we can use to test the accuracy and reliability of the script. Iridium flares are easily predicted, allowing one to prepare to collect their data. NASA data can provide a steady source of fireball events to access along with their data to compare to. Finally, fireball events detected by D6 will be tested.

4.1 Iridium Flares

The first step in testing out the script is to run it in conjunction with video collected directly from D6. A simple way to do this is to run it against a video clip of an Iridium flare that D6 captured. There are two benefits of testing against an Iridium flare. First, Iridium flares are predicted online and their maximum magnitudes are recorded. We can find the maximum value from our light curve and compare it to the known maximum magnitude. Second, the light curves from Iridium flares are very smooth, and the flare moves a minimal amount, reducing risk of errors due to tracking. This makes it easy to notice any discrepancies in individual frames. We have collected two Iridium flare events using D6.

In late November of 2017, D6 was able to capture an Iridium flare going over Collins Hall at Willamette University in Salem, Oregon. The first frame of this event is shown as Figure 4.1. The program was then run on this event's footage. Its created light curve can be seen in Figure 4.2. The first thing to check is if it qualitatively agrees with visual inspection of the event's video. The light curves shown in Figure 4.2 agree with that. So in a qualitative sense, the photometry program is capable of tracking the event and measuring its light.

Some issues did emerge from this event, however. Ideally, we would like to be able to compare the maximum magnitude from the light curve our program created to the recorded maximum magnitude of the event. Unfortunately, the Iridium flare was so bright that it oversaturated our camera. This can be seen in Figure 4.3. Figure 4.3 allows us to see that the center of event is too bright for



Figure 4.1: The first Iridium flare captured by D6 at Willamette University can be seen in the lower right quadrant.

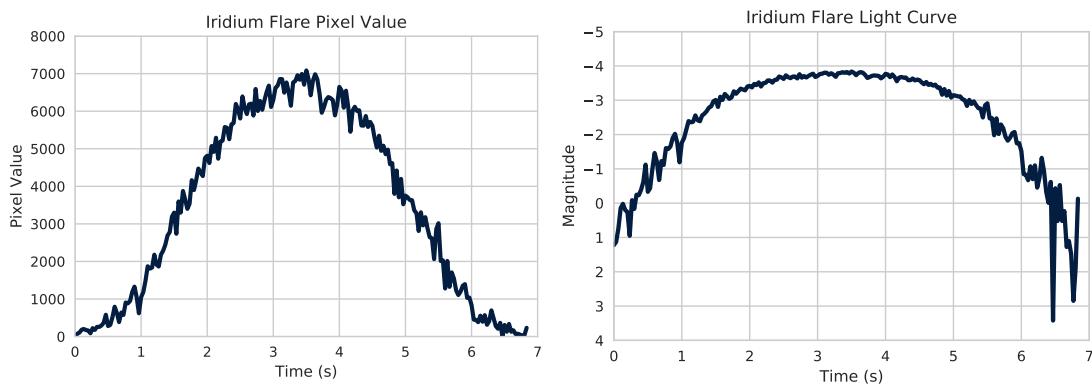


Figure 4.2: While light curves are usually displayed in terms of magnitude, it is important to remember the source of those magnitude values: pixel values.

our camera's sensors. As a result, we are unable to find the current maximum magnitude of that Iridium flare event. This saturation also explains why the peaks in Figure 4.2 last for a substantial portion of the event; the true peak brightness is not visible on those graphs. As a result, this light curve would be underestimating the true peak brightness of the flare.

Another issue that is apparent in the Iridium flare data is noise appearing in sections of the data. Specifically, the noise at the end of the event appears most jarring in Figure 4.2 after the logarithm is applied. When the event nears its end, the signal to noise ratio greatly decreases. This noise is a result of the background light that has already been mentioned. Since the event is at its end, it has become incredibly dim, and in its last moments its signal is basically equal to the background light around it. Since the background light value we are using is the average of the area around the event, there arises occasions where

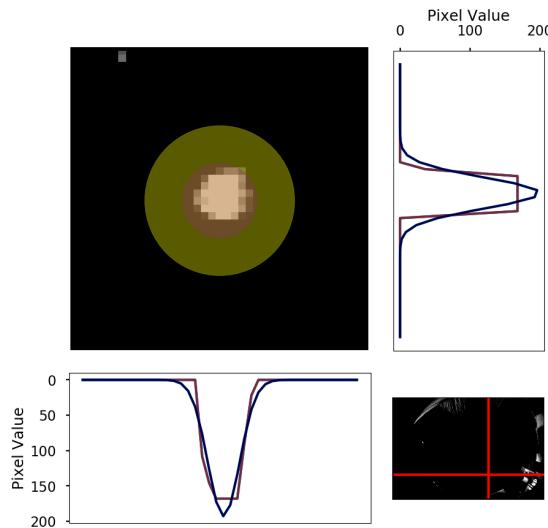


Figure 4.3: The X and Y data slices are plotted alongside the object. The peak of the event flattens out, when one would expect it to curve at the top, similar to the Gaussian curves fitted upon the data.

the pixels of the event are smaller than the background light at this stage. This creates a magnitude that is the resultant of a log of an incredibly small, or even negative number. Since taking the logarithm of a negative error is mathematically impossible, those values are set to 0. So, at the end of an event before the program no longer detects any trace of the flare, the last data points are very small, and that smallness is magnified by the logarithm.

Iridium flares are somewhat useful pseudo-meteors, but ultimately the program needs to show that it can successfully track actual meteors. When running the program on an Iridium flare event the tracking algorithm is not challenged greatly; the flare's light was at a relatively constant position on the camera's frames. Meteor events that do move far across the screen pose a new challenge for the program that needs testing.

4.2 Comparison to NASA Data

The methods section provided an example of a light curve acquired from our program using a NASA video clip. By running the script against videos of events recorded by NASA, we can confirm that the script is working by comparing it to NASA's accompanying light curves. The collected data and results of this test are discussed below.

The first event we acquired from NASA's database was one that occurred on March 21, 2018, by one of their cameras stationed in Central Florida. The video

was downloaded alongside their infographic of data involving the event. This infographic, displayed as Figure 4.4, contains the light curve of the event in the top right corner. In order to convert that picture of the light curve to a dataset we can work with, the light curve was run through a plot digitizer to extract the numerical data and convert it to a CSV file. The CSV file was then read into Python using the Pandas package where their magnitude results were stored alongside ours in a Pandas DataFrame.

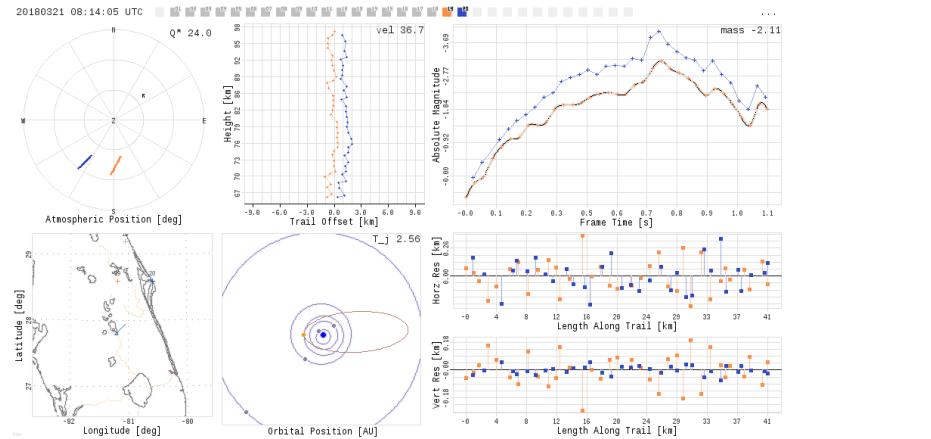


Figure 4.4: The light curve NASA attained off the same video is shown in orange in the top right of the graphic [NAS].

While the light curve is crucial to compare our results to, the infographic also contains other crucial information for star calibration such as the video’s location, the event’s direction, and the time of the event. This allows us to make use of planetarium software to view how the stars were positioned and oriented so we can identify a valid reference star. For our purposes, we used Stellarium. Stellarium is a free, open-source¹ planetarium software available on all major operating systems².

With Stellarium, we were able to obtain a view of the position of celestial objects at that time, as seen in Figure 4.5. The Stellarium image in Figure 4.5 was then compared to the thresholded video frames of the event in order to try to identify one of the brighter objects. Assuming the Stellarium view was positioned correctly, celestial objects should appear to be in the same place in both images. A few pieces of data can be extracted from the two images. The only piece of data that we need is the magnitude of a single object, which can be obtained by clicking on that object in Stellarium. For this calibration, Jupiter was used with its magnitude of -2.35 at the time. Another piece of data that can be extracted is

¹Open-source projects are one the best catalysts of intelligent thought in a society. If possible, they should be used at all costs.

²Available on most, but perhaps not all, Linux distributions.



Figure 4.5: The thresholded image with labels added next to identified objects, next to the Stellarium image it was compared to.

that the event in question was most likely from the θ -Virginids or π -Virginids, as the event is in the same area as those two meteor showers were happening on that day. This is another piece of strong evidence that the sky is oriented correctly in the images.

Now that we had a celestial object with a magnitude to calibrate to, the program was run on the event. When it finished, the end result is the magnitude of each frame plotted over the time of the event, showing the light curve of the event. The light curve of this event from the program is shown in Figure 4.6. The general trend shows that program's methodology in calculating the magnitude is sound. We would expect the brightness to gradually grow before diminishing again, and the graph agrees with that. As previously mentioned, this event was detected off of one of NASA's cameras so we can compare our light curve to NASA's to double check. NASA's light curve can also be seen in Figure 4.6. The light curves' general shapes align well.

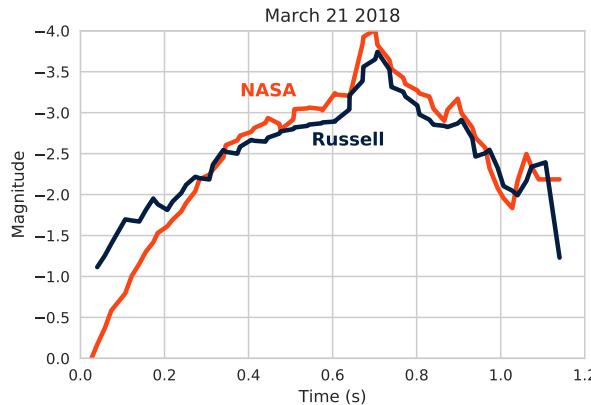


Figure 4.6: The light curves from the program and from NASA. The NASA light curves are not calibrated, so they are shifted up for easier comparison purposes.

One aspect of the data that does not seem to fit well is the beginning of the event. This can be seen quantitatively by plotting the residuals of the two data sets and looking for outliers, which is done in Figure 4.7. The difference in the two plots can also be displayed with the use of a violin plot, shown in Figure 4.8. This allows us to see whether it is overestimating or underestimating the magnitude by looking at the top and bottom of the plot. By accounting for the offset, those outliers are not masked underneath a consistent offset the data may have.

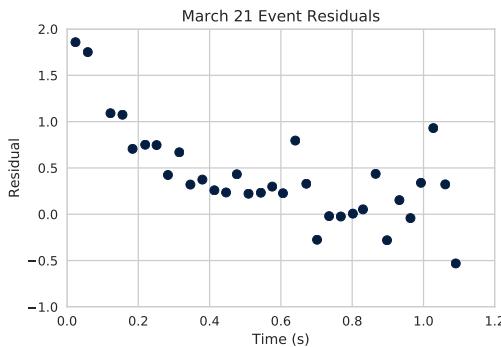


Figure 4.7: The residuals are randomly distributed except at the very beginning of the event. Ideally, they would be completely randomly distributed.

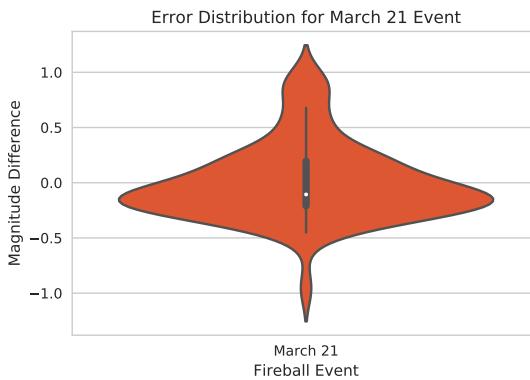


Figure 4.8: A violin plot can show the residuals in a histogram-like form. Here, we can see the majority of the residuals are close to zero as that is where the bulk of the violin is.

Light curve comparisons and the responding violin plots were then made for other events pulled from NASA's all-sky camera network. The light curves are shown in Figure 4.9. Again, it should be stated that the Y-axes of these graphs are shifted magnitudes, as the NASA light curves were shifted up for comparison purposes once again.

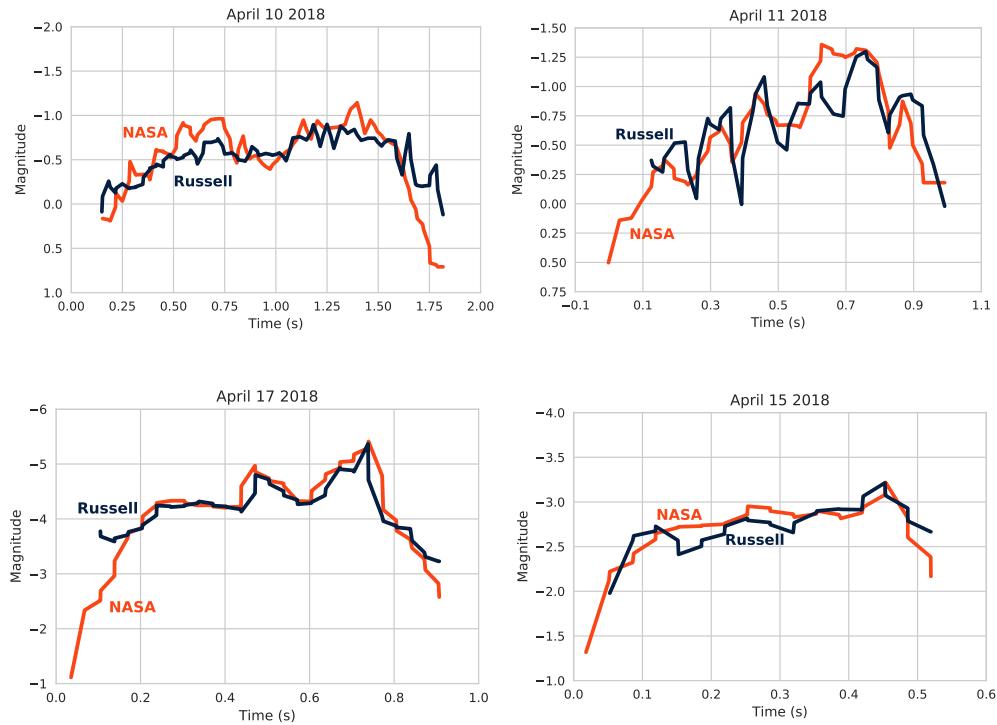


Figure 4.9: Light curves collected over multiple events. The general patterns match well in all four, but a few have smaller-scale discrepancies.

The choppiness of some of the curves, specifically the one for the April 11 event, makes it somewhat difficult to see how much the two light curves agree with each other. As a result, violin plots were made for the datasets again. Those violin plots can be seen in Figure 4.10. The results were generally in agreement with each other, with a few points being outliers once again, specifically for the events on March 21 and April 10. In order to get a general idea on the accuracy for the data in the aggregate, Figure 4.10 also shows the combined violin plot of all the events. Once again, there are a few outliers, but in general the data agree with each other, with the majority of the points being within 0.5 magnitude in either direction of the mean.

Most of the plots show a few data points do not agree with NASA's light curve. This discrepancy may be because the program does not take into account parameters such as atmospheric extinction³. These parameters are more influential if the object moves radially across the night sky in the camera's frame. If NASA did take into account this effect, then that would explain some of the difference.

³This is discussed as a problem to address in the Chapter 5.

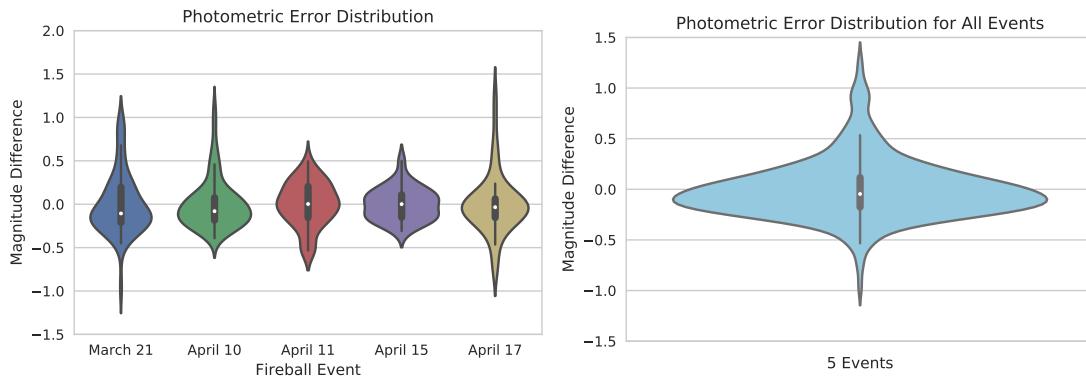


Figure 4.10: The violin plot for all these events have a few outliers, mostly in overestimation.

4.3 Fireballs Detected with D6

Ultimately, however, the goal of our research is to show our all-sky camera is a viable alternative to previously established systems. Therefore, the final test of the photometry script is the ability for it to analyze new data collected from our own all-sky camera. With self-collected data, however, there are often problems that require troubleshooting. One problem that emerged is a result of the interlacing of the video signal. Essentially, every other column or row is processed and merged together. This occasionally results in frames that are visually confusing, as seen in Figure 4.11. This, while visually unappealing, does not actually affect the pixel summation.

The resulting light curve is still far from being exactly correct, however, as shown in Figure 4.12. This is another possible example of what happens often when we are analyzing a dim event: there is a very low signal to noise ratio. This event just happened to be a particularly dim one, which is not a great starting point for troubleshooting problems. For this reason, along with the previously mentioned ones, this fireball event is not a strong test sample.

Unfortunately, D6 is in the process of having an operating system overhaul in an attempt to fix some internal library issues preventing its computer from running the necessary code to detect the fireballs. The program will have to wait until D6's operating system is finished updating before getting another attempt at in-house data.

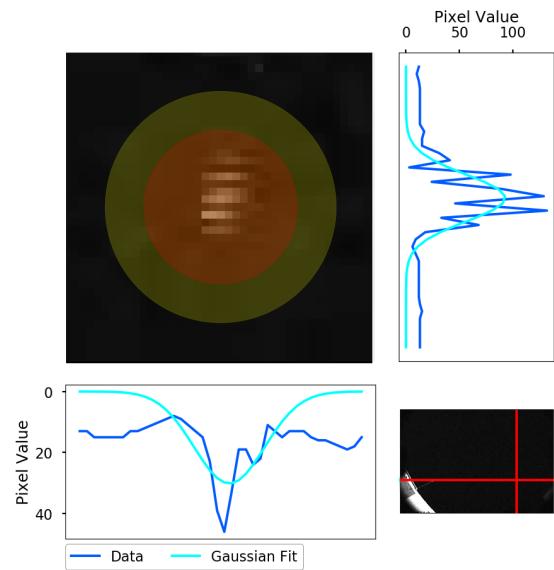


Figure 4.11: The interlacing effect makes it appear as if the data is corrupted, as it looks as if there are empty rows in the array.

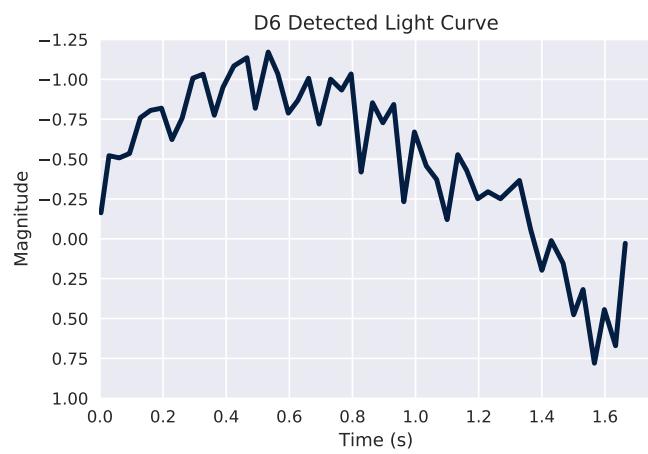


Figure 4.12: The light curve of this event is much less smooth than one would expect from a fireball.

5 Conclusion

So what does the data show us regarding the current capabilities of our all-sky camera setup? There are improvements to be made, problems to troubleshoot, but on a wholistic sense, the system and software seems most assuredly capable of photometrically analyzing the events.

5.1 Critique

One potentially problematic issue is there is currently no way for us to compare our calibrated light curves to other calibrated magnitudes. Each of the potential ways to do so are somewhat flawed in one aspect or the other. Comparing our data to NASA's allows us to effectively see if the shape of our light curve is accurate, but as their posted data is uncalibrated to a reference object, we cannot confirm our calibration. The other source of comparison is the Iridium flare data. The Iridium flare data does not have light curves to compare to but they do have posted maximum magnitudes. Unfortunately, as mentioned in the data section, our camera cannot see that maximum magnitude in most Iridium flare events due to oversaturation. For future events, it would be worthwhile to attempt at adjusting the sensitivity levels of the camera. The only other option would be extrapolating the peaks from the Gaussian curves, but that creates more accuracy issues as previously mentioned.

In order to confirm our calibration is accurate, we should find data sets with calibrated magnitudes and posted video clips to compare to. However, it is worth noting that if the program can detect the shape of the light curve accurately, which it has repeatedly shown it can, it should have no problem with the calibration. After all, the calibration is dependent on the same algorithm, only it arises from the calculation of the reference star's magnitude instead of the object's magnitude. In fact, it should be even easier to do so, as the reference star does not move throughout the duration of the event; the program does not need to update the position it is covering.

There is also potentially more data to gain from the reference objects as well. As mentioned in the Chapter 4, there are often multiple reference objects seen in the video. Calibrating off of multiple reference objects would give us greater confidence in the calibration capabilities. As those objects' magnitudes should be constant throughout the event, their light curves could also allude to the margin of error in our light curves depending on how nonlinear their light curves appear.

5.1.1 Atmospheric Extinction

Further examination is needed to figure out whether or not the discrepancies at the beginning of the light curve is based off a correctable parameter such as atmospheric extinction, or whether it arises from a systematic failure in the program to successfully find the magnitudes of dimmer objects.

We most likely will have to account for atmospheric extinction. Atmospheric extinction, visualized in 5.1, is a phenomenon caused by different areas of the sky having different amounts of air between them and the observer. As a result, a meteor near the horizon is separated by more air, and thus appears dimmer than if the same meteor was right above the observer.

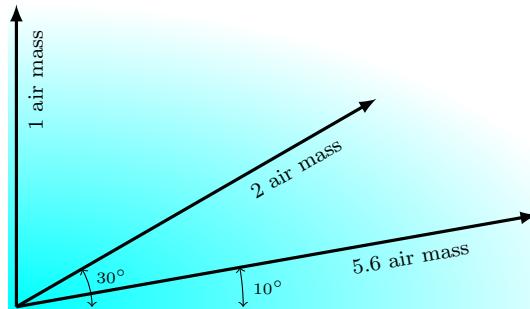


Figure 5.1: There is more air in between someone and an object along the horizon than an object directly above them.

5.2 Outlook

This project is far from being completed. Creating a program that successfully analyzes meteor events is the most important building block for collecting data, but there is much more to do beyond that. Now that the script is set up, a substantial number of events would need to be collected with our own all-sky camera to be able to make any reasonable conclusions about the near-Earth population. If we are able to do so, we are then able to show that a setup similar to D6 is a viable alternative to the larger setups currently in place. The data that is needed to be

collected is the photometric data of the events, but there is substantial statistical analysis that needs to be done to extrapolate that photometric data into meteor size. The future of this project is thus based on optimizing the data collected and analyzing that data to justify drawing any reasonable conclusion.

A Python Packages

The code used in the process of performing this research was done in Python. The actual code can be found in Appendix B. It contains the script used to analyze the data after it was collected, the script used to acquire the photometric data, and the script used to create the graphic user interface. An integral part of all three scripts were the use of Python packages in their implementation. A description of those packages are described, while the rest of the code should hopefully be self-explanatory.

Pandas

Pandas is a software library that can create table-like data structures for basically any type of data. It is really great for consolidating all one's data in one **Pandas DataFrame**, and makes it extremely simple to pull certain parts of that data for analysis. For this project, all of the time and magnitude data for both NASA and our own light curves for all events were thrown into a **DataFrame** and then pieces of the data were used for the plots found in the Chapter 4.

NumPy

NumPY is a softare library that makes manipulating lists substantially easier. The majority of the lists used in the process of the photometric analysis script were NumPy arrays.

SciPy

SciPy is an incredibly powerful library that can solve and deal with many parts of mathematical equations. The photometric analysis script used this power for fitting Gaussian curves to the data.

OpenCV

OpenCV is a computer vision library available in multiple languages. Without **OpenCV**, it would not be possible to analyze the data from the videos and their frames, as it pulls in that data.

Matplotlib and Seaborn

Matplotlib is a library for plotting data, and **Seaborn** improves upon that library. The majority of the plots in Chapter 4, along with the frame visuals in the Chapter 3, were plotted with **Matplotlib**. **Seaborn**'s styles and themes were applied to those plots as **Matplotlib**'s ability in that regard is limited, and its default colors are a poor choice, especially for readers with partial or full color-blindness.

Tkinter

Tkinter is one of the most popular GUI toolkits for Python. It was used to create and organize the graphic user interface that allows the user to run the photometry script. Its functions make up the bulk of the GUI script in Appendix B.

B Code

B.1 Data Analysis

```

1  #Packages
2  %matplotlib inline
3  import matplotlib.pyplot as plt
4  import numpy as np
5  import seaborn as sns
6  import pandas as pd
7
8  #Function
9  def Plotting(NasaCSV, OursCSV, TimeOffset, Date):
10     Nasa = pd.read_csv(NasaCSV)
11     Nasa = Nasa.set_index('Time')
12
13     Ours = pd.read_csv(OursCSV)
14     Ours.Time += TimeOffset
15     Ours = Ours.set_index('Time')
16
17     FireballData = Nasa.join(Ours, rsuffix='0', how='outer').interpolate()
18     FireballData['dM'] = FireballData.Mag - FireballData.Mag0
19     FireballData['YOffset'] = FireballData.dM.mean()
20     FireballData['Magnitude Difference'] = (FireballData.dM.dropna() - FireballData.dM.mean())
21     FireballData['AdjustedMag'] = (FireballData.Mag0 + FireballData.YOffset)
22     FireballData['Fireball Event'] = Date
23
24     return(FireballData)

```

B.2 Photometry Script

```

1 import seaborn as sns
2 import numpy as np
3 import cv2
4 import argparse
5 import math
6 import matplotlib.pyplot as plt
7 from scipy.optimize import curve_fit
8 import matplotlib.gridspec as gridspec
9 import matplotlib
10 from PIL import Image
11
12 END = False
13 REFERENCESTARLOC = (0,0)
14 OBJECTLOC = (0,0)
15 OBJECTAVGRADIUS = 0
16 OBJECTBACKGROUNDADIUS = 0
17 REFERENCESTARAVGRADIUS = 0
18 REFERENCEBACKGROUNDADIUS = 0
19 XFitParametersRef = []
20 YFitParametersRef = []
21 XFitParametersObj = []
22 YFitParametersObj = []
23
24 matplotlib.rcParams['figure.figsize']=(10,10)
25
26 ######
27 # Inputs: Video, Click Coordinates, OpenCV Jazz
28 # Returns: N/A
29 # Sets locations = to left and right click
30 #####
31 def click(event, x, y, flags, param):
32     global REFERENCESTARLOC
33     global OBJECTLOC
34     if event == cv2.EVENT_LBUTTONDOWN:
35         REFERENCESTARLOC = (x,y)
36     elif event == cv2.EVENT_RBUTTONDOWN:
37         OBJECTLOC = (x,y)
38
39 #####
40 # Inputs: Image, XY from click or previous frame

```

```

41  # Returns: New XY
42  # Applies Contour to find new center
43 #####
44 def MaxFinder(X, Y, img):
45     global END
46
47     r = 10
48     subimg = img[Y-r:Y+r, X-r:X+r]
49     blur = cv2.GaussianBlur(subimg, (5,5), 0)
50     thresh = cv2.threshold(blur, 50, 255, cv2.THRESH_BINARY)[1]
51     thresh = Threshold(blur, THRESHOLDNUMBER)
52     im2, contours, heir = cv2.findContours(thresh, cv2.RETR_TREE,
53                                         cv2.CHAIN_APPROX_SIMPLE)
54
55     areas = [cv2.contourArea(c) for c in contours]
56     if not areas:
57         END = True
58         return
59     max_idx = np.argmax(areas)
60     cnt = contours[max_idx]
61
62     M = cv2.moments(cnt)
63     if M["m00"] == 0:
64         M["m00"] = 1
65
66     if M["m00"] != 0:
67         cX = int(M["m10"] / M["m00"])
68         cY = int(M["m01"] / M["m00"])
69         MaxLocShifted = (X-r+cX, Y-r+cY)
70     else:
71         MaxLocShifted = (X-r,Y-r)
72     return MaxLocShifted
73
74 #####
75 # Defining mathematical eq for Gaussian Finder
76 #####
77 def Gaussian(x, a, x0, Sigma):
78     return a*np.exp(-(x-x0)**2/(2*Sigma**2))
79
80 #####
81 # Inputs: Contour Coordinates, Frame
82 # Returns: x0, Sigma, a of Gaussian fit

```

```

83 # Used twice, 1 for X, 1 for Y
84 #####
85 def GaussianFinder(MaxLoc, img):
86     CoordinatesX = []
87     CoordinatesY = []
88     Range = np.arange(MaxLoc-10,MaxLoc+10)
89
90     if MaxLoc == REFERENCESTARLOC[0]:
91         Coordinates = img[REFERENCESTARLOC[1], MaxLoc-10:MaxLoc+10]
92     if MaxLoc == REFERENCESTARLOC[1]:
93         Coordinates = img[MaxLoc-10:MaxLoc+10, REFERENCESTARLOC[0]]
94     if MaxLoc == OBJECTLOC[0]:
95         Coordinates = img[OBJECTLOC[1], MaxLoc-10:MaxLoc+10]
96     if MaxLoc == OBJECTLOC[1]:
97         Coordinates = img[MaxLoc-10:MaxLoc+10, OBJECTLOC[0]]
98
99     Mean = MaxLoc
100    Sigma = 3
101    try:
102        FitParameters, pcov = curve_fit(Gaussian, Range, Coordinates,
103                                         p0 = [np.max(Coordinates), Mean, Sigma])
104    except RuntimeError:
105        FitParameters = [np.max(Coordinates),Mean, Sigma]
106
107    return(FitParameters)
108
109 #####
110 #Inputs: Gaussian parameters & location, Frame
111 #Returns: Sum of Pixels in Radius
112 #####
113 def MagnitudeFinder(Loc, XFitParameters, YFitParameters, img):
114     global Radius, OBJECTBACKGROUNDADIUS, REFERENCEBACKGROUNDADIUS
115     global OBJECTAVGRADIUS, REFERENCESTARAVGRADIUS
116     YRadius = int(np.ceil(2*XFitParameters[2]))
117     XRadius = int(np.ceil(2*YFitParameters[2]))
118     Radius = max(XRadius,YRadius)
119
120     Range=[]
121     if Radius > 100:
122         Radius = 100
123     for i in range(-Radius,Radius):
124         for j in range(-Radius,Radius):

```

```

125         if i**2 + j**2 < Radius**2:
126             Range.append((i + Loc[0], j + Loc[1])[::-1])
127
128     BackgroundRadius = Radius+5
129     BackgroundRange = []
130     for i in range(-BackgroundRadius,BackgroundRadius):
131         for j in range(-BackgroundRadius,BackgroundRadius):
132             if i**2 + j**2 < BackgroundRadius**2 and \
133                 i**2 + j**2 > Radius**2:
134                 BackgroundRange.append((i + Loc[0], j + Loc[1])[::-1])
135
136     BackgroundValues = []
137     for i in BackgroundRange:
138         BackgroundValues.append(img[i])
139     AvgBackgroundMag = sum(BackgroundValues)/len(BackgroundValues)
140     MagValue = 0
141     RawMagValue = 0
142     for i in Range:
143         MagValue = MagValue + (img[i] - AvgBackgroundMag)
144         RawMagValue = RawMagValue + img[i]
145     if Loc == REFERENCESTARLOC:
146         REFERENCESTARAVGRADIUS = Radius
147         REFERENCEBACKGROUNDADIUS = Radius+5
148     if Loc == OBJECTLOC:
149         OBJECTAVGRADIUS = Radius
150         OBJECTBACKGROUNDADIUS = Radius+5
151     return(MagValue)
152
153 #####Inputs: Gaussian, Radius, Frame, Usermade Folder#####
154 #Creates Plot for each frame with Gaussians
155 #####
156 def PlottingCurve(XFitParameters, YFitParameters, Radius, img, Folder):
157     ZR
158
159     def getPlotSlice(XCent, YCent, Dir, PlotRange):
160         """Function to return a single column or row sliced at
161             the desired location
162             and in the desired direction.
163             XCent and YCent are integers and Dir is a stringof either "x" or "y"
164             """
165
166         # Gaussian positions are not integers so converting to integers
167         # Extracting desired slice

```

```

167     if Dir == 'x':
168         return img[YCent,XCent-PlotRange:XCent+PlotRange]
169     else:
170         return img[YCent-PlotRange:YCent+PlotRange, XCent]
171
172     XMaxLoc = int(XFitParameters[1])
173     YMaxLoc = int(YFitParameters[1])
174
175     # sns.set()
176     # sns.set_style("dark")
177     sns.set_context("poster")
178     matplotlib.style.use("dark_background")
179     gs = gridspec.GridSpec(2, 2, width_ratios=[2, 1], height_ratios=[2,1])
180     ax = plt.subplot(gs[0, 0])
181
182     ax1 = plt.subplot(gs[0])
183     ax2 = plt.subplot(gs[1])
184     ax3 = plt.subplot(gs[2])
185     ax4 = plt.subplot(gs[3])
186
187     PlotRange = 20
188
189     #Top Left
190     ax1.imshow(img,cmap='gray')
191     if XMaxLoc == int(XFitParametersObj[1]):
192         ax1.set_xlim(-PlotRange+OBJECTLOC[0],PlotRange+OBJECTLOC[0])
193         ax1.set_ylim(-PlotRange+OBJECTLOC[1],PlotRange+OBJECTLOC[1])
194         ax1.add_artist(plt.Circle((OBJECTLOC),OBJECTBACKGROUNDADIUS,
195             color = 'yellow', alpha=.2))
196         ax1.add_artist(plt.Circle((OBJECTLOC),OBJECTAVGRADIUS,color='red',
197             alpha=.2))
198     if XMaxLoc == int(XFitParametersRef[1]):
199         ax1.set_xlim(-PlotRange+REFERENCESTARLOC[0],
200                     PlotRange+REFERENCESTARLOC[0])
201         ax1.set_ylim(-PlotRange+REFERENCESTARLOC[1],
202                     PlotRange+REFERENCESTARLOC[1])
203         ax1.add_artist(plt.Circle((REFERENCESTARLOC),5,
204             color='blue', alpha=0.2))
205         ax1.add_artist(plt.Circle((REFERENCESTARLOC),REFERENCEBACKGROUNDADIUS,
206             color = 'yellow', alpha=.2))
207     ax1.axis('off')
208

```

```

209 #Top Right
210 if YMaxLoc == int(YFitParametersObj[1]):
211     ax2.plot(getPlotSlice(OBJECTLOC[0], OBJECTLOC[1], 'y', PlotRange),
212             np.arange(-PlotRange+OBJECTLOC[1], PlotRange+OBJECTLOC[1], 1),
213             label='Data', color='orange')
214     ax2.plot((Gaussian(np.arange(-PlotRange+OBJECTLOC[1],
215                         PlotRange+OBJECTLOC[1], 1), *YFitParameters)),
216             np.arange(-PlotRange+OBJECTLOC[1], PlotRange+OBJECTLOC[1], 1),
217             label='Gaussian Fit', color='red')
218     ax2.set_xlabel('Pixel Value')
219 if YMaxLoc == int(YFitParametersRef[1]):
220     ax2.plot(getPlotSlice(REFERENCESTARLOC[0], REFERENCESTARLOC[1],
221                         'y', PlotRange),
222             np.arange(-PlotRange+REFERENCESTARLOC[1],
223                     PlotRange+REFERENCESTARLOC[1], 1),
224             label='Data')
225     ax2.plot((Gaussian(np.arange(-PlotRange+REFERENCESTARLOC[1],
226                         PlotRange+REFERENCESTARLOC[1], 1), *YFitParameters)),
227             np.arange(-PlotRange+REFERENCESTARLOC[1],
228                     PlotRange+REFERENCESTARLOC[1], 1),
229             label='Gaussian Fit')
230     ax2.yaxis.set_visible(False)
231     ax2.xaxis.tick_top()
232     ax2.xaxis.set_label_position('top')
233
234 #Bottom Left
235 if XMaxLoc == int(XFitParametersObj[1]):
236     ax3.plot(np.arange(-PlotRange+OBJECTLOC[0], PlotRange+OBJECTLOC[0]),
237             getPlotSlice(OBJECTLOC[0], OBJECTLOC[1], 'x', PlotRange),
238             label='Data', color='orange')
239     ax3.plot(np.arange(-PlotRange+OBJECTLOC[0], PlotRange+OBJECTLOC[0]),
240             Gaussian(np.arange(-PlotRange+OBJECTLOC[0],
241                         PlotRange+OBJECTLOC[0]), *XFitParameters),
242             label='Gaussian Fit', color='red')
243     ax3.set_ylabel('Pixel Value')
244 if XMaxLoc == int(XFitParametersRef[1]):
245     YMaxLoc = REFERENCESTARLOC[1]
246     XMaxLoc = REFERENCESTARLOC[0]
247     ax3.plot(np.arange(-PlotRange+XMaxLoc, PlotRange+XMaxLoc),
248             getPlotSlice(XMaxLoc, YMaxLoc, 'x', PlotRange),
249             label='Data')
250     ax3.plot(np.arange(-PlotRange+XMaxLoc, PlotRange+XMaxLoc),

```

```

251         Gaussian(np.arange(-PlotRange+XMaxLoc,PlotRange+XMaxLoc),
252                     *XFitParameters),
253                     label='Gaussian Fit')
254 ax3.invert_yaxis()
255 ax3.xaxis.set_visible(False)
256
257 #Bottom Right
258 ax4.imshow(img,cmap='gray')
259 if XMaxLoc == int(XFitParametersObj[1]):
260     ax4.axvline(OBJECTLOC[0], color='red')
261     ax4.axhline(OBJECTLOC[1], color='red')
262 if XMaxLoc == int(XFitParametersRef[1]):
263     ax4.axvline(REFERENCESTARLOC[0], color='blue')
264     ax4.axhline(REFERENCESTARLOC[1], color='blue')
265 ax4.axis('off')
266
267
268 plt.subplots_adjust(wspace=.1)
269 plt.subplots_adjust(hspace=.1)
270 plt.draw()
271
272 if XFitParameters[0] == XFitParametersObj[0]:
273     plt.savefig(f'{Folder}/ObjectPlot{Iteration:03d}.png',
274                 bbox_inches='tight')
275 if XFitParameters[0] == XFitParametersRef[0]:
276     plt.savefig(f'{Folder}/ReferencePlot{Iteration:03d}.png',
277                 bbox_inches='tight')
278
279 #####
280 # Inputs: Current Frame, Current Slider Value
281 # Returns: Thresholded Frame
282 # Used for threshold slider in GUI
283 #####
284 def Threshold(theimage, ThresholdRatio):
285     threshold = cv2.threshold(theimage, ThresholdRatio, 255,
286                               cv2.THRESH_BINARY)[1]
287     return(threshold)
288
289 #####
290 # Input: User selected video
291 # Returns: Video for GUI
292 #####

```

```

293 def InitialRead(VideoName):
294     Array = np.array([],ndmin=3)
295     Video = cv2.VideoCapture(VideoName)
296     print(VideoName)
297     Grabbed, TheImage = Video.read()
298     TheImage = cv2.cvtColor(TheImage, cv2.COLOR_BGR2GRAY)
299     ImageStack = TheImage
300     (Grabbed,TheImage) = Video.read()
301     while Grabbed == True:
302         TheImage = cv2.cvtColor(TheImage, cv2.COLOR_BGR2GRAY)
303         ImageStack = np.dstack([ImageStack,TheImage])
304         (Grabbed,TheImage) = Video.read()
305     return(ImageStack)
306
307 ######
308 # Inputs: video, folder to save stuff, what frame
309 #           user clicks, threshold, star value
310 # Where the looping and running happens
311 #####
312 def main(vid_name,Folder,StartFrame, objectlocation, referencestarlocation,
313           ThresholdNumber,TheCatalogMagnitude):
314     global REFERENCESTARLOC
315     global OBJECTLOC
316     global REFERENCESTARAVGRADIUS
317     global OBJECTAVGRADIUS
318     global OBJECTBACKGROUNDGRADIUS
319     global REFERENCEBACKGROUNDGRADIUS
320     global THRESHOLDNUMBER
321     global XFitParametersRef
322     global YFitParametersRef
323     global XFitParametersObj
324     global YFitParametersObj
325     global CatalogMagnitude
326     global Iteration
327     global ObjectMagValue
328
329     record = True
330     frame_no = 100
331     CatalogMagnitude = float(TheCatalogMagnitude) #parameter cant be global
332
333     REFERENCESTARLOC = referencestarlocation
334     OBJECTLOC = objectlocation

```

```

335     THRESHOLDNUMBER = ThresholdNumber
336
337     vid = cv2.VideoCapture(vid_name)
338     vid.set(1,StartFrame);
339     Grabbed, img = vid.read()
340     img = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)
341
342     blurred = cv2.GaussianBlur(img, (5, 5), 0)
343     Thresh = cv2.threshold(blurred, 60, 255, cv2.THRESH_BINARY)[1]
344
345     # REFERENCESTARLOC = MaxFinder(REFERENCESTARLOC[0],
346     # REFERENCESTARLOC[1], img)
347     # XFitParametersRef = GaussianFinder(REFERENCESTARLOC[0], img)
348     # YFitParametersRef = GaussianFinder(REFERENCESTARLOC[1], img)
349     # ReferenceMagValue = MagnitudeFinder(REFERENCESTARLOC,
350         # GaussianFinder(REFERENCESTARLOC[0], img),
351         # GaussianFinder(REFERENCESTARLOC[1], img), img)
352     # XFitParameters = (0,0,0)
353
354     ObjectMagValueList = []
355     ReferenceMagValueList = []
356     CatalogList = []
357     Instrument = []
358     Iteration = 1
359     while Grabbed == True:
360
361         (Grabbed, img) = vid.read()
362         if Grabbed == False:
363             break
364         img = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)
365
366         REFERENCESTARLOC = MaxFinder(REFERENCESTARLOC[0],
367             REFERENCESTARLOC[1], img)
368         if END == True:
369             break
370         XFitParametersRef = GaussianFinder(REFERENCESTARLOC[0], img)
371         YFitParametersRef = GaussianFinder(REFERENCESTARLOC[1], img)
372         ReferenceMagValue = MagnitudeFinder(REFERENCESTARLOC,
373             GaussianFinder(REFERENCESTARLOC[0], img),
374             GaussianFinder(REFERENCESTARLOC[1], img), img)
375         ReferenceMagValueList.append(ReferenceMagValue)
376

```

```

377     OBJECTLOC = MaxFinder(OBJECTLOC[0], OBJECTLOC[1], img)
378     if END == True:
379         break
380     XFitParametersObj = GaussianFinder(OBJECTLOC[0], img)
381     YFitParametersObj = GaussianFinder(OBJECTLOC[1], img)
382     ObjectMagValue=MagnitudeFinder(OBJECTLOC,XFitParametersObj,
383                                     YFitParametersObj, img)
384     if ObjectMagValue < 0:
385         ObjectMagValue = 0
386     ObjectMagValueList.append(ObjectMagValue)
387
388     PlottingCurve(XFitParametersObj, YFitParametersObj, OBJECTAVGRADIUS,
389                   img,Folder)
390     PlottingCurve(XFitParametersRef, YFitParametersRef,
391                   REFERENCESTARAVGRADIUS, img,Folder)
392     Iteration += 1
393
394     ReferenceMagValue = np.mean(ReferenceMagValueList)
395
396     InstrumentalMagnitude = -2.5*np.log10(ReferenceMagValue)
397     Offset = InstrumentalMagnitude - CatalogMagnitude
398
399     for i in ObjectMagValueList:
400         ObjectCatalogValue = -2.5*np.log10(i) - Offset
401         CatalogList.append(ObjectCatalogValue)
402
403     with open(f'{Folder}/MagValues.txt', 'w') as output:
404         output.write(str(ObjectMagValueList))
405     with open(f'{Folder}CatalogValues.txt', 'w') as output:
406         output.write(str(CatalogList))
407
408     plt.figure()
409     plt.plot(np.arange(0,len(CatalogList)),CatalogList)
410     plt.xlabel('Frame')
411     plt.ylabel('Magnitude')
412     # plt.yticks([])
413     plt.gca().invert_yaxis()
414     plt.savefig(f"{Folder}/LightCurve.png", bbox_inches='tight')
415
416 ######
417 # open with "python /path/to/script.py --image /path/to/picture.jpg"
418 #####

```

```

419 if __name__ == "__main__":
420     ap=argparse.ArgumentParser()
421     ap.add_argument("-i", "--video", required=True)
422     args= vars(ap.parse_args())
423     main(args['video'])

```

B.3 GUI Script

```

1  import tkinter as tk
2  from tkinter.filedialog import askopenfilename
3  import tkinter.ttk as ttk
4  from tkinter.constants import *
5  from PIL import Image, ImageTk
6  import glob
7  import Photometry
8  import os
9  import sys
10 import shutil
11 import time
12 import datetime
13 import numpy as np
14 import cv2
15
16
17 class GUI(tk.Frame):
18
19     @classmethod
20     def main(cls):
21         root = tk.Tk()
22         app = cls(root)
23         app.grid(sticky=NSEW)
24         root.geometry('800x500+50+50')
25         root.grid_columnconfigure(0, weight=1)
26         root.grid_rowconfigure(0, weight=1)
27         root.mainloop()
28
29     def __init__(self, root):
30         super().__init__(root)
31         self.master = root
32         self.pack(fill=BOTH, expand=True)
33

```

```

34         self.tk_setPalette( background = 'black',
35                               foreground = 'gray80',
36                               activeBackground = 'gray30',
37                               selectColor = 'firebrick4',
38                               selectBackground = 'firebrick4' )
39
40     self.createWidgets()
41
42 #####
43 # Organizing/Placing Widgets
44 #####
45 def createWidgets(self):
46     self.Plotted = False
47     self.ObjectClick = False
48     self.ReferenceClick = False
49     self.ThresholdToggle = False
50     self.FrameNo = 1
51     self.ThresholdCompleted = False
52     self.ChoiceToggle = False
53
54 #####
55 Frame1 = tk.Frame(self)
56 Frame1.pack(fill=X)
57 #####
58 self.FolderName = tk.Entry(Frame1)
59 self.FolderName.insert(0,
60                     f'{datetime.datetime.now().strftime("%Y%m%d_%H%M")}')
61 self.FolderName.pack(side=LEFT, fill=Y)
62
63 self.runButton = tk.Button(Frame1, text='RUN', width=7,
64                           height=1, command=self.run, bg='black', state=DISABLED)
65 self.runButton.pack(side=LEFT)
66
67 self.openButton = tk.Button(Frame1, text='OPEN', width=7,
68                           height=1, command=self.open, bg='black')
69 self.openButton.pack(side=LEFT)
70
71 self.restartButton = tk.Button(Frame1, text='RESET', width=7,
72                           height=1, command=self.restart, bg='black')
73 self.restartButton.pack(side=LEFT)
74
75 self.QuitButton = tk.Button(Frame1, text="QUIT",

```

```

76             command=Frame1.quit, width=7)
77 self.QuitButton.pack(side=LEFT)
78
79 ######
80 Frame2 = tk.Frame(self)
81 Frame2.pack(fill=X)
82 #####
83 self.NameButton = tk.Button(Frame2, text="POSITION", width=7)
84 self.NameButton.pack(side=LEFT)
85
86 self.Choice=tk.IntVar()
87 self.ObjectLabel = tk.Radiobutton(Frame2, text="Object: ( X , Y )",
88                                 variable=self.Choice, value=0, indicatoron=0,
89                                 command=self.ObjectChoice)
90 self.ReferenceLabel = tk.Radiobutton(Frame2,
91                                     text="Reference Star: ( X , Y )", variable=self.Choice, value=1,
92                                     indicatoron=0,command=self.ObjectChoice)
93 self.ObjectLabel.pack(side=LEFT,fill=Y)
94 self.ReferenceLabel.pack(side=LEFT,fill=Y)
95
96 self.CatalogValue = tk.Entry(Frame2)
97 self.CatalogValue.insert(0, '0')
98 self.CatalogValue.pack(side=LEFT, fill=Y)
99
100 #####
101 Frame2_1 = tk.Frame(self)
102 Frame2_1.pack(fill=X)
103 #####
104 self.ThresholdButton = tk.Button(Frame2_1, text="THRESHOLD", width=7)
105 self.ThresholdButton.pack(side=LEFT)
106
107 self.ThresholdVariable=tk.IntVar()
108 self.ThresholdOn = tk.Radiobutton(Frame2_1, text="ON",
109                                 variable=self.ThresholdVariable, value=1, indicatoron=0,
110                                 command=self.ThresholdRadio)
111 self.ThresholdOff = tk.Radiobutton(Frame2_1,
112                                     text="OFF", variable=self.ThresholdVariable, value=0,
113                                     indicatoron=0, command=self.ThresholdRadio)
114 self.ThresholdOn.pack(side=LEFT,fill=Y)
115 self.ThresholdOff.pack(side=LEFT,fill=Y)
116
117 #####

```

```

118     Frame3 = tk.Frame(self)
119     Frame3.pack(fill=X)
120     #####
121     self.CamView = []
122     self.canvas = tk.Canvas(Frame3, width = 720, height=480, bg='black')
123     self.canvas.pack(side=LEFT)
124     self.ImageCanvas= self.canvas.create_image(0,0, anchor=NW,
125         image=self.CamView)
126     self.canvas.bind("<Button-1>",self.ReferenceCoordinates)
127     self.canvas.bind("<Button-3>",self.ObjectCoordinates)
128
129     self.LightCurve = tk.Label(Frame3, image="")
130     self.LightCurve.pack(side=LEFT)
131
132     self.display = tk.Label(Frame3, image="")
133     self.display.pack(side=LEFT)
134
135     #####
136     Frame4 = tk.Frame(self)
137     Frame4.pack(fill=X)
138     #####
139     self.slidervar = tk.IntVar()
140     self.InitialSlider = tk.Scale(Frame4, from_=0, to=100,
141         orient=HORIZONTAL, label='Initial Frame',
142         command=self.VideoLength, variable=self.slidervar,length=360)
143     self.InitialSlider.pack(side=LEFT)
144
145     self.thresholdvar = tk.IntVar()
146     self.ThresholdSlider = tk.Scale(Frame4, from_=0, to=255,
147         orient=HORIZONTAL, label='Threshold',
148         command=self.Threshold,variable=self.thresholdvar,length=360)
149     self.ThresholdSlider.pack(side=LEFT)
150
151     self.var = tk.IntVar()
152     self.FrameSlider = tk.Scale(Frame4, from_=1, to=2,
153         orient=HORIZONTAL, length = 360, command=self.PlotFrame,
154         variable=self.var, label='Plot Frame' )
155     self.FrameSlider.pack(side=LEFT)
156
157     #####
158     # Functions for Widgets
159     #####

```

```

160     def PlotFrame(self,event):
161         FrameNumber = self.var.get()
162         if self.ChoiceToggle == False:
163             print('False')
164             PlotPath= f'{self.FolderPath}/ObjectPlot{FrameNumber:03}.png'
165             self.PlotImage = Image.open(PlotPath)
166             self.PlotImage = self.PlotImage.resize((360,360),Image.ANTIALIAS)
167             self.PlotImage = ImageTk.PhotoImage(self.PlotImage)
168             self.display.config(image=self.PlotImage)
169         if self.ChoiceToggle == True:
170             print('True')
171             PlotPath= f'{self.FolderPath}/ReferencePlot{FrameNumber:03}.png'
172             self.PlotImage = Image.open(PlotPath)
173             self.PlotImage = self.PlotImage.resize((360,360),Image.ANTIALIAS)
174             self.PlotImage = ImageTk.PhotoImage(self.PlotImage)
175             self.display.config(image=self.PlotImage)
176
177     def ReferenceCoordinates(self,event):
178         self.ReferenceLabel.configure(text=f"Reference: ({event.x},{event.y})")
179         self.REFERENCESTARLOC = (event.x,event.y)
180         self.ReferenceLabel.configure(bg ='white',fg = 'black')
181         self.ReferenceClick = True
182         if self.ObjectClick == True and self.ThresholdCompleted == True:
183             self.runButton.config(state='normal')
184
185     def ObjectCoordinates(self,event):
186         self.ObjectLabel.configure(text=f"Object: ({event.x},{event.y})")
187         self.OBJECTLOC = (event.x,event.y)
188         self.ObjectLabel.configure(bg ='white',fg = 'black')
189         self.ObjectClick = True
190         if self.ReferenceClick == True and self.ThresholdCompleted == True:
191             self.runButton.config(state='normal')
192
193     def ObjectChoice(self):
194         if self.Choice.get() == 0:
195             print('0')
196             self.ChoiceToggle = False
197         if self.Choice.get() == 1:
198             print('1')
199             self.ChoiceToggle = True
200
201     def ThresholdRadio(self):

```

```

202     self.ThresholdSelection = self.ThresholdVariable.get()
203     if self.ThresholdSelection == 0:
204         self.ThresholdToggle = False
205     if self.ThresholdSelection == 1:
206         self.ThresholdToggle = True
207
208     def VideoLength(self,event):
209         self.FrameNo = self.slidervar.get()
210         if self.ThresholdToggle == False:
211             self.CamView = Image.fromarray(self.ImageStack[:, :, self.FrameNo])
212             self.CamView = ImageTk.PhotoImage(self.CamView)
213             self.canvas.itemconfig(self.ImageCanvas,image=self.CamView)
214         if self.ThresholdToggle == True:
215             self.ThresholdCompleted = True
216             self.ThresholdNumber = self.thresholdvar.get()
217             ThresholdView = Photometry.Threshold(self.ImageStack[:, :, 
218                                         self.FrameNo], self.ThresholdNumber)
219             self.CamView = Image.fromarray(ThresholdView)
220             self.CamView = ImageTk.PhotoImage(self.CamView)
221             self.canvas.itemconfig(self.ImageCanvas,image=self.CamView)
222
223     def Threshold(self,event):
224         self.ThresholdToggle = True
225         self.ThresholdNumber = self.thresholdvar.get()
226         ThresholdView = Photometry.Threshold(self.ImageStack[:, :, self.FrameNo], 
227                                         self.ThresholdNumber)
228         self.CamView = Image.fromarray(ThresholdView)
229         self.CamView = ImageTk.PhotoImage(self.CamView)
230         self.canvas.itemconfig(self.ImageCanvas,image=self.CamView)
231         self.ThresholdCompleted = True
232
233     def open(self):
234         self.VideoName = tk.filedialog.askopenfilename(initialdir = 'Data')
235         self.VideoPath = '/'.join(self.VideoName.split('/')[-1:])
236         self.FolderDirectory = (self.FolderName.get())
237         self.FolderPath = f'{self.VideoPath}/{self.FolderDirectory}'
238         if os.path.exists(self.FolderPath):
239             shutil.rmtree(self.FolderPath)
240             os.makedirs(self.FolderPath)
241
242         self.ImageStack = Photometry.InitialRead(self.VideoName)
243         VideoSize = self.ImageStack.shape[2]

```

```

244     self.InitialSlider.config(to=VideoSize-1)
245     self.CamView = Image.fromarray(self.ImageStack[:, :, 0])
246     self.CamView = ImageTk.PhotoImage(self.CamView)
247     self.canvas.itemconfig(self.ImageCanvas, image=self.CamView)
248     self.openButton.configure(bg='white', fg='black')
249
250 def run(self):
251     self.Catalog = self.CatalogValue.get()
252     Photometry.main(self.VideoName, self.FolderPath, self.FrameNo,
253                     self.OBJECTLOC, self.REFERENCESTARLOC,
254                     self.ThresholdNumber, self.Catalog)
255     lightcurvepath= f'{self.FolderPath}/LightCurve.png'
256     self.OG = Image.open(lightcurvepath)
257     ResizedOG = self.OG.resize((360,240),Image.ANTIALIAS)
258     self.IMG = ImageTk.PhotoImage(ResizedOG)
259     self.LightCurve.config(image=self.IMG)
260     self.runButton.configure(bg = 'white', fg='black')
261     MaxFrameNumber= len(glob.glob(f'{self.FolderPath}/ObjectPlot*.png'))
262     self.FrameSlider.config(to=MaxFrameNumber)
263     self.restartButton.configure(bg ='firebrick4')
264
265     FrameNumber = self.var.get()
266     PlotPath= f'{self.FolderPath}/ObjectPlot{FrameNumber:03}.png'
267     self.PlotImage = Image.open(PlotPath)
268     self.PlotImage = self.PlotImage.resize((360,360),Image.ANTIALIAS)
269     self.PlotImage = ImageTk.PhotoImage(self.PlotImage)
270     self.display.config(image=self.PlotImage)
271
272 def restart(self):
273     python = sys.executable
274     os.execl(python, python, * sys.argv)
275
276 if __name__ == '__main__':
277     GUI.main()

```

Bibliography

- [Alc] Alcor, *OMEA All Sky Camera*.
- [Ban12] Steven Bannister, *New Calibration Technique for All Sky Cameras*, Ph.D. thesis, New Mexico State University, 2012, p. 152.
- [Bot07] WF Bottke, *Understanding the near-Earth object population: the 2004 perspective*, Comet/asteroid Impacts and Human Society: An Interdisciplinary Approach (Hans Rickman Peter T. Bobrowsky, ed.), no. 2003, Springer-Verlag Berlin Heidelberg, 2007.
- [BVRN06] William F. Bottke, David Vokrouhlický, David P. Rubincam, and David Nesvorný, *THE YARKOVSKY AND YORP EFFECTS: Implications for Asteroid Dynamics*, Annual Review of Earth and Planetary Sciences **34** (2006), no. 1, 157–191.
- [ESA17] ESA, *Hypervelocity Impacts and Protecting Spacecraft*, 2017.
- [Har08] Jennifer Harbaugh, *Intro to Meteors and the NASA All-Sky Camera Network, The Fireball Project*, 2008.
- [HGB96] Ian Halliday, Arthur A. Griffin, and Alan T. Blackwell, *Detailed data for 259 fireballs from the Canadian camera network and inferences concerning the influx of large meteoroids*, Meteoritics & Planetary Science **31** (1996), no. 2, 185–217.
- [Jen06] Peter Jenniskens, *Meteor Showers and their Parent Comets*, 2006.
- [JGD⁺11] P. Jenniskens, P.S. Gural, L. Dynneson, B.J. Grigsby, K.E. Newman, M. Borden, M. Koop, and D. Holman, *CAMS: Cameras for Allsky Meteor Surveillance to establish minor meteor showers*, Icarus **216** (2011), no. 1, 40–61.
- [MG05] S. Molau and P.S. Gural, *A review of video meteor detection and analysis software*, WGN **33** (2005), 15–20.

- [MM95] Michèle Moons and Alessandro Morbidelli, *Secular Resonances in Mean Motion Commensurabilities: The 4/1, 3/1, 5/2, and 7/3 Cases*, Icarus **114** (1995), no. 1, 33–50.
- [NAS] NASA, *NASA's All Sky Fireball Network*.
- [R R17] T.J. Jopek R Rudawska, Z Kanuchova, *Meteor Data Center list of Meteor Showers*, 2017.
- [RR15] J. Jedediah Rembold and Eileen V. Ryan, *Characterization and Analysis of Near-Earth Objects via Lunar Impact Observations*, Planetary and Space Science **117** (2015), 119–126.
- [SEM17] R. M. Suggs, S. R. Ehlert, and D. E. Moser, *A comparison of radiometric calibration techniques for lunar impact flashes*, Planetary and Space Science **143** (2017), 225–229.
- [Sky] LLC SkySentinel, *SkySentinel Network*.
- [SMCS14] R. M. Suggs, D. E. Moser, W. J. Cooke, and R. J. Suggs, *The flux of kilogram-sized meteoroids from lunar impact monitoring*, Icarus **238** (2014), 23–36.
- [Ste96] Duncan Steel, *Meteoroid orbits*, Space Science Reviews **78** (1996), no. 3-4, 507–553.
- [TRML⁺07] Josep M. Trigo-Rodríguez, José M. Madiedo, Jordi Llorca, Peter S. Gural, Pep Pujols, and Tunc Tezel, *The 2006 Orionid outburst imaged by all-sky CCD cameras from Spain: meteoroid spatial fluxes and orbital elements*, Monthly Notices of the Royal Astronomical Society **380** (2007), no. 1, 126–132.
- [TRMW⁺09] Josep Ma Trigo-Rodríguez, José M. Madiedo, Iwan P. Williams, Alberto J. Castro-Tirado, Jordi Llorca, Stanislav Vítek, and Martin Jelínek, *Observations of a very bright fireball and its likely link with comet C/1919 Q2 Metcalf*, Monthly Notices of the Royal Astronomical Society **394** (2009), no. 1, 569–576.
- [Whi51] Fred Whipple, *A Comet Model. II. Physical Relations for Comets and Meteors*, Astrophysical Journal **113** (1951), 464.