Cosmic Debris through the Lens: Exploring Space Debris Detection with Long Exposure Photography using the Fujifilm X-T3

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Abstract

Space debris, remnants of defunct satellites, spent rocket stages and other discarded materials, pose a growing threat to our orbital environment. Yet, traditional techniques of tracking and observation have been unsuccessful in mapping the majority of this debris, due in part to their overwhelming and ubiquitous presence in the Low Earth Orbit (LEO) ecosystem, which extends up to 2000 km above sea level. In this paper, we present an alternative approach for detecting large debris fragments using the Fujifilm X-T3, a Digital Single-Lens Reflex (DSLR) camera popular with professionals and enthusiasts alike. The goal is to optimize tracking resources, allowing observatories to concentrate on less conspicuous debris. Through repeated imaging of the night sky, active cross-referencing with known satellite flybys, and photometric analysis, we will investigate the feasibility and potential of monitoring space debris with a consumer product currently available on the market. Results from images have shown evidence of visible space debris, demonstrating the feasibility of debris detection with modest equipment and the prospects of citizen science in advancing current tracking methods.

1. Introduction

1.1 General Introduction

Since the launch of the first artificial satellite[1] in 1957, Earth's orbit has become the setting stage for a range of crucial planetary activities, including telecommunications (Jamalipour & Tung, 2001), ground navigation in the form of the Global Positioning System (GPS) (Lechner & Baumann, 2000), and climate research and monitoring (Yang et al., 2013), among others. However, with this increased flurry of orbital activity, there followed an accumulation of intact yet obsolete infrastructure, mostly nonfunctional satellites, spent rocket thrusters and even miscellaneous items such as, according to Klinkrad (2016), "screwdrivers and protective gloves [lost] during extravehicular activities of astronauts(...)". These objects, collectively known as space debris, pose an increasing threat to existing functional satellites in orbit (National Research Council, 1995), ground infrastructure, and the general public (Byers et al., 2022). Due to their immense speeds in orbit, often well exceeding 10 km/s

[1] Sputnik 1, launched on October 4, 1957 as part of the Soviet space program.

(Goldstein et al., 1998), space debris is at a high risk of generating additional debris through high-impact collisions with other objects. This phenomenon is known as a fragmentation event (Lewis et al., 2011), which is responsible for the majority of space debris proliferation in Low Earth Orbit (LEO) since the 1960s (Figure 1).

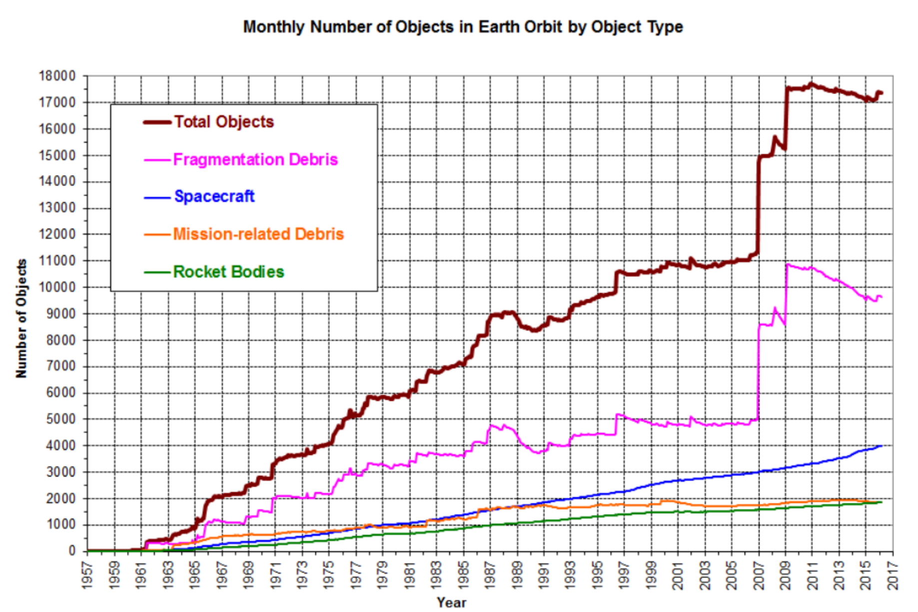

Figure 1 - Estimated number of Objects in Earth Orbit per month by Object Type, 1957-2016. Adapted from *Measuring small debris – what you can't see can hurt you* by M. Matney, 2016 (https://ntrs.nasa.gov/api/citations/20160011225/downloads/20160011225.pdf)

As our planet's orbit becomes increasingly crowded with space debris, innovative methods are essential for detecting and monitoring these potentially hazardous objects. While most debris is microscopic and invisible to currently available surveillance methods, many larger debris are detectable to ground-based tracking methods, including radar imaging, optical imaging and LiDAR (Beaulieu, 2022). In this research paper, we explore the application of interval photography as a powerful tool for identifying and tracking space debris. Specifically, we focus on leveraging the capabilities of the Fujifilm X-T3, a camera renowned for its relative affordability and popularity as a go-to camera for budding photographers (Lawton, 2020).

To our knowledge, this paper will be the first to explore the suitability of the Fujifilm X-T3 for the detection of orbital debris. We will delve into the technical aspects of interval photography, explore various photographic settings and discuss the implications for space debris monitoring. Our findings will aim to advance our understanding of space debris dynamics and inform strategies for safeguarding our vital space infrastructure.

1.2 Linear Photometry

In astronomy, photometry (from the Greek *phōs* for "light" and *métron* for "measure") is the branch of science concerned with measuring the intensity of light emitted or reflected by astronomical objects (Sterken & Manfroid, 1992). For the purposes of this study, a nonstandard form of photometry was employed to analyze the apparent brightness of orbital trails. This method, called linear photometry, considers the flux of light along a straight line on an image plane. This is especially useful for trails, which are approximately straight lines.

2. Methodology

2.1 Photographic Methods

Two primary methods were used to collect a sufficient number of images (henceforth known as "datasets") for the purpose of this study, namely long interval and short interval photography. Long interval photography (where the time interval between individual shots was 20 seconds) was initially used, accounting for the majority of data collected with this method. The last few datasets were however captured using short interval photography (time interval 1 second). This change was made following the realization that photometric analysis was more compatible with the first method. Regardless, both forms of photography provided ample information about the night sky and orbital trails.

In both methods, photographs of the night sky were taken during astronomical twilight at Wreck Beach on the University of British Columbia's Vancouver campus. The photos were layered together through use of the astrophotography software StarStaX, creating an exposure of star, satellite, and debris trails that were able to be categorized and analyzed.

2.2 Equipment

The Fujifilm X-T3, a digital single-lens reflex camera with a 16 mm lens, with a field of view (FOV) of 108°, was used to take all the photographs for this study. ("Specifications," n.d.) The lens aperture was set to the maximum aperture for the equipment available, which would allow for most dimmer objects to be captured without excessively increasing digital noise through other means of brightening the image. The camera's shutter speed was set so each frame of the final composed image captured up to 1 second of movement across the night sky. The International Organization for Standardization (ISO) sensitivity was set depending on the conditions for each night, taking into account ability to capture dim objects and minimization of noise introduced by atmospheric scattering at the horizon and distant city lights. Common astrophotographical knowledge was used as an initial baseline (Mallory Davis Photography, 2023), after which on-site experience was prioritized for determination of technical photographical choices. See appendix for specific settings.

2.3 Astronomical set-up

Astronomical twilight was chosen as the time of day for which data would be collected as it is when the sun is at a range of 12° to 18° below the horizon such that reflective objects in LEO will be able to reflect sunlight to Earth (Žilková et al., 2023). The camera was pointed towards the zenith on a tripod as that allowed for the shortest distance between the lens and expected flight trajectories, thereby simplifying trigonometric calculations. As mentioned above, photos were taken at Wreck Beach due to its relatively mild light pollution (Bortle 7 [2]), allowing for better visibility of incident space debris. The cardinal directions were accounted for when cross-referencing with satellite databases.

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[2] The Bortle scale is a numeric scale, running from 1 to 9, that measures the intensity of background light pollution of an observer site. 9 indicating the most polluted sky, we measured a Bortle scale of 7 with a set of qualitative criteria, such as the absence of the Milky Way and the faint visibility of M31 in the sky.

2.4 Data collection procedure

The first method was the one that was used to collect most datasets; however, only one ended up being viable for analysis. Due to the intervals between individual shots being 20 seconds long, as well as the camera's FOV, candidates for space debris would typically only show up a few times in each frame of the stacked images, generally spaced far apart.

The second method was developed through incorporating the experience gained through the first method. The primary difference was a decrease in the interval of time between shots, from 20 seconds to 1 second. This decrease allowed for more continuous lines present in the stacked photographs, thereby allowing more confidence in determining whether streaks in the sky were potential candidates for space debris.

Figure 2 - Image obtained through method 1 (left) vs. image obtained through method 2 (right). Distinct candidate trails are shown in the image on the right. Trails are easily discernible from stars, which move radially around a point off image (i.e. the North pole) Own work.

Data analysis was accomplished through use of three tactics: object speed analysis for ruling out non-orbiting objects (see *3.1.1*), photometry for determining between non-registered satellites and potential debris (see *3.1.2*), and database cross-referencing for ruling out registered satellites and finding confirmed debris (see *3.1.3)*. A combination of these analytical methods was used to determine the occurrence of space debris in each image.

3. Data and Results

3.1 Data analysis

Eleven datasets (image stacks) were collected over four clear nights between February 12 and February 26, 2024, of which three were deemed viable. A set of three criteria was applied to analysis and identification of potential space debris:

1. The geometrical analysis of potential orbital speeds of trails, known as speed analysis (3.1.1);
2. The computational analysis of apparent magnitude, or brightness, of trails over time or distance, known as photometry (3.1.2); and,
3. Corroborating sightings with predicted fly-bys of registered satellites and debris in orbit, using public databases that draw on NORAD element sets, known as cross-referencing (3.1.3).

3.1.1 Speed analysis

This approach involved filtering trail sightings for objects orbiting Earth, predominantly satellites and debris, technically known as resident space objects (RSO). RSOs display characteristic speeds associated with their altitude in Earth's orbit, since the likes of meteors travel faster than debris and satellites by an appreciable amount (Hill, 2019). These speeds are determined by the use of orbital velocity equation $v = \sqrt{\frac{GM}{r}}$. Speeds that deviate significantly from the calculated baseline would indicate that the object cannot sustain itself in orbit—too-fast objects would escape Earth's gravitational pull and too-slow objects would enter the atmosphere.

Secondly, the apparent lengths of trails in the datasets indicated the distance covered by the object. This was determined geometrically through a series of valid approximations and through knowledge of the camera's FOV. Once the possible range of speeds were calculated for a given length of trail, they were plotted along with the model equation above. If the two plots intersected at some altitude and velocity for an object, they plausibly suggested an RSO. Otherwise, they were ruled out as extraorbital bodies, like an asteroid or comet, and not counted in the project survey. See Appendix B for the corresponding codebase.

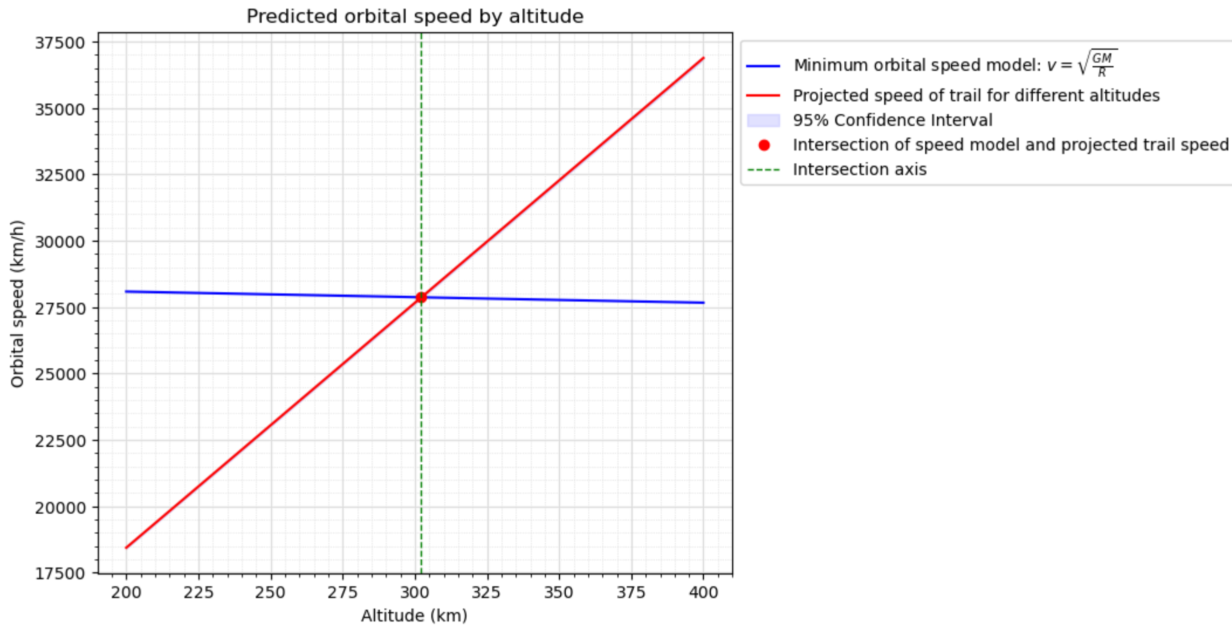

Figure 2 - Example plot of minimum orbital speed model plotted with projected speed of a candidate trail at different altitudes. Intersection point is made easier to see through plotting the intersection axis; final determination was outputted by the code, to more precision, at 27,886 km/h with an altitude of 302.25 km. Own work.

3.1.2 Photometric Analysis

Satellites tend to exhibit very regular patterns of light while in orbit. Space debris, however, exhibit fluctuations in brightness over time due to their tendency to "tumble" in orbit, therefore enabling the use of photometry analysis to further filter candidates (Cipollone et al., 2022). The AstroimageJ program, developed by the University of Louisville, was used to find grayscale values for each pixel of the trail, and objects with no periodic change in grayscale value, corresponding to their brightness, were assumed not to be space debris unless direct cross-referencing suggested otherwise.

This approach was only applicable for a subset of datasets, namely those obtained through short interval photography, which allowed for a more continuous trail.

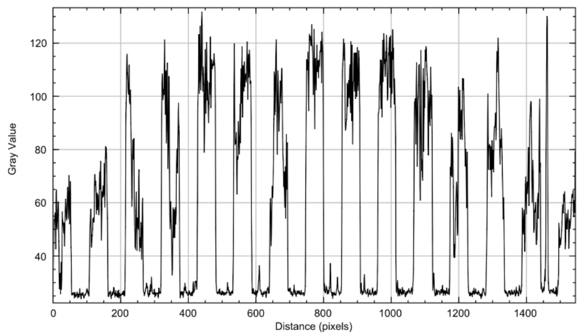	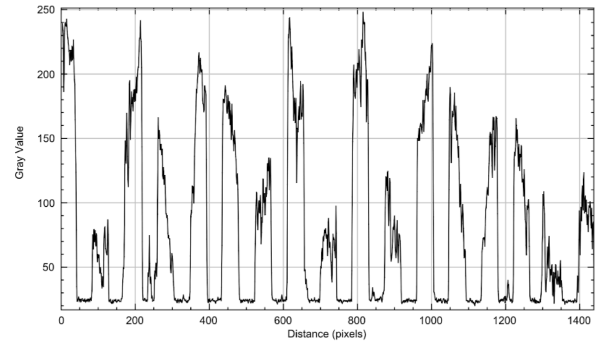
Figure 4: Grayscale vs. Distance graph for a short-interval satellite trail. Aside from regular dips, caused by the period during which no photo was taken, a clear rise and fall trend is visible. Generated by AstroImageJ. Own work.	Figure 5: Grayscale vs. Distance graph for a short-interval debris trail. Aside from regular dips, caused by the period during which no photo was taken, a clear periodic change in grayscale value is visible. Generated by AstroImageJ. Own work.

3.1.3 Cross-Referencing

Candidates were cross-referenced with the satellite elements from the North American Aerospace Defense Command (NORAD) database, as well as checked against Stellarium. These two measures enabled the filtering out of most satellite objects, comets, and meteors, as well as direct determination of debris in some cases. However, some military satellites are not in official registries making it difficult to cross-reference with candidates found. (Hecht, 2001) Therefore, there is some uncertainty in the actual number of space debris found; the resulting estimate of amounts of space debris using the experimental method detailed in this study could be an overestimate. Unexplained trails could potentially be due to these untracked objects and not just untracked space debris, which is why photometry was helpful in filtering candidates.

3.2 Results

Of the eleven datasets, only three were found to be viable for data analysis of potential debris trails. Two of these three datasets, taken on February 26, 2024, were obtained through short-interval photography. The third was taken on February 13 through long-interval photography. Across these three datasets, thirty-six trails (henceforth known as “candidate” trails) were identified and were subjected to a combination of speed analysis, photometric profiling and cross-referencing with

NORAD elements. Only the two datasets from February 26 were suitable for photometric analysis. These were the results of the three aforementioned analyses:

- Notwithstanding orbital eccentricities, all thirty-six candidates were estimated to have altitudes consistent with orbits in low-Earth orbit (LEO) or very low-Earth orbit (VLEO) .
- Eight of the candidates were ruled out as satellites through cross-referencing. Another two were however confirmed to be space debris. This leaves twenty-six candidates whose identities and origins are unknown.
- Of the twenty-six unidentified candidates, only six (all from the February 26 datasets) were recorded to show clear photometric signatures. Of these six, only one had an oscillatory presentation consistent with space debris trails.

In summary, only two candidates were confirmed to be space debris and another was inconclusive but showed positive indicators for space debris. See Appendix A for tabulated details about candidates.

4. Discussion

4.1 Implications

Through this study, it has been demonstrated that it is possible to use the DSLR long exposure functionality to photograph and determine space debris in the night sky. This is promising for making this field of science more accessible to the general public, since DSLRs are a highly accessible tool that many public citizens may already have. However, there is still a degree of inaccuracy in the overall estimation of space debris using this method. Thus, before any strong considerations are made about using this method for professional debris detection, it is imperative to more strictly understand the limitations of the technique, as well as find solutions and methods of improvement.

4.2 Errors and Limitations

A number of approximations and assumptions were made during data analysis. For one, orbiting objects were assumed to exhibit perfectly regular and circular orbits. This allowed for simpler calculation of orbital speeds. On the other hand, this did not reflect the true orbits of the vast majority of RSOs. Eccentric orbits that might highly influence the apparent speed and altitude of an object would distort the results.

Orbital speed calculations had limitations as well. Meteors at altitudes where their trajectory matched that of debris in LEO could have been included in the final tally, giving the illusion of an untracked, highly irregularly-shaped object that might imitate key characteristics of space debris (although this has not been confirmed in literature). Thus, speed analysis is not a definitive tool and must accompany photometry and cross-referencing practices to ensure reliability.

Further, approximation was undertaken for a trail's arc length subtended at Earth's center to a line tangent to the target's orbit at or around the zenith, allowing for the application of geometry to determine the distance traveled in a known period of time. In such an approximation, it does not matter where the line is "subtended", unlike the arc length whose value is dependent on the product of the radius and sector angle of a circle centered in the Earth. The Earth was assumed to be perfectly spherical, also for the purposes of making calculations less complex. This is illustrated by Figure 3 below.

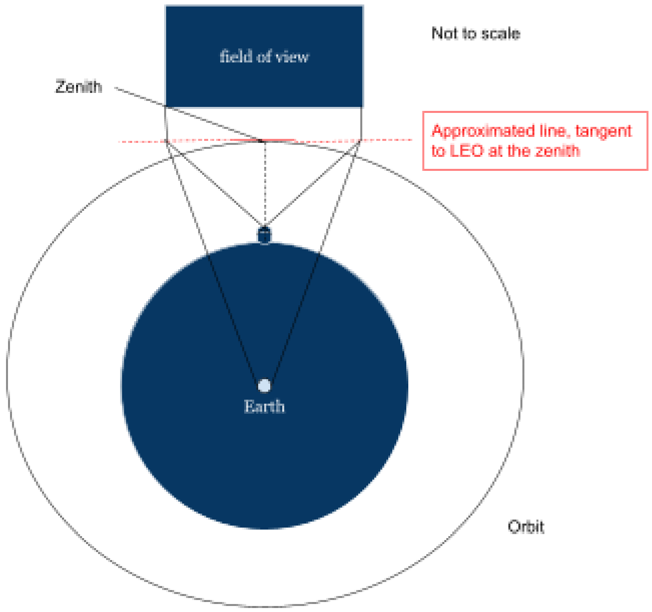

Figure 3 - Approximation made for the arc subtended at Earth's center to a straight light tangent to the orbit at the zenith. Own work.

There were a number of factors that could have made the results less conclusive; this included planes passing overhead and atmospheric effects. Firstly, cross-referencing of candidates with flight path databases was excluded from the data analysis. As most planes passing through the FOV would have been taking off or landing at C-YVR, Vancouver's airport, any planes within datasets were assumed to be low enough to appear as three adjacent lines, as pictured in Figure 4 below. Non-star objects that did not exhibit this pattern, therefore, were determined to be candidates for space debris.

Figure 4 - Composite image of a plane's trail captured within a dataset, surrounded by star trails. Three red lines are shown, corresponding to a total of three visible tail and wing lights. Own work.

Atmospheric distortions such as atmospheric pressure differences and refraction of light at different angles could have led to variance in the grayscale values detected within a trail, mimicking the tumbling pattern of debris. Furthermore, the software used was not appropriately calibrated for changes in background light pollution over small time intervals, such as background light caused by campfires or nearby sea vessels.

4.3 Further research

Any further research would primarily fulfill the purpose of improving accuracy and standardization of technique, as well as more specifically determining limitations. For example, at this point in time it is uncertain what size of debris is visible by the camera. Furthermore, due to changing conditions between photographs, ISO must continuously be tweaked; future research may investigate a standardization method that would more properly allow for maximum number of trails photographed while ensuring the data is of good quality. Finally, it may be possible to apply trajectory models to spotted debris, therefore enabling the long-term tracking of debris and potential refining of current trajectory models.

5. Concluding Remarks

Space debris detection with a commercial digital camera, such as the Fujifilm X-T3, is a viable technique to further debris tracking and catalog efforts. Further research and funding can help explore the feasibility and benefits of leveraging support from the general public in identifying space debris. This raises tantalizing prospects for further development in mapping the full extent of debris and, eventually, contribute towards finding a solution for managing orbital debris in the not-so-distant future.

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7. Appendix A (Images and Data tables)

7.1 Camera settings

Overall Settings

Lens	16 mm
ISO	1600-3200
Aperture	F-1.4

Method 1 Specific Settings (Used for Dataset C)

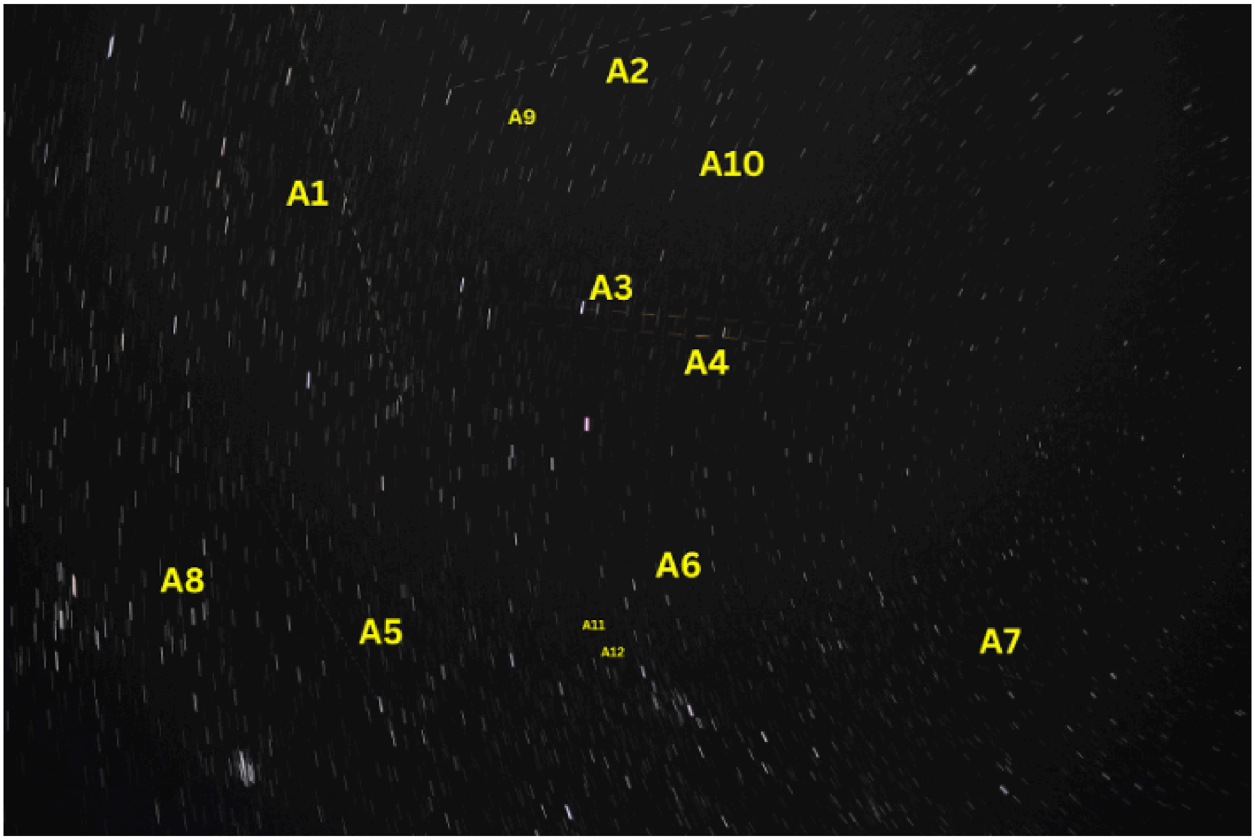
Interval between each shot	20 seconds
Shutter speed	1 second

Method 2 Specific Settings

Dataset A	**Interval between each shot**	1 second
	Shutter speed	1 second
Dataset B	**Interval between each shot**	1 second
	Shutter speed	0.5 seconds

7.2 Images + datasets

Dataset A (February 26, 2024)



Candidate	Altitude (km)	Speed (km/h)	Photometric profile?	Identity
A1	*684.31*	*27,099*	*Yes (oscillating quickly)*	*Unknown*
A2	569.16	27,324	Yes	Unknown
A3	443.37	27,575	Yes	Unknown
A4	436.96	27,588	Yes	Unknown
A5	1503.1	25,647	Yes (oscillating slowly)	Globalstar 60
A6	**1878.9**	**25055**	**Yes**	**Anik-F1R BrzTnk (NORAD 28870)**

A7	**452.25**	**27557**	**Yes**	**Dbl Star LM Rk (NORAD 28448)**
A8	667.66	27131	No (too dim)	Starlink 4592
A9	105	28289	No (WAY too dim)	Starlink 1606
A10	536.14	27389	Yes	Unknown
A11	564.37	27333	No (too dim)	Unknown
A12	586.22	27290	No (too dim)	Unknown

*Bolded are confirmed to be space debris.

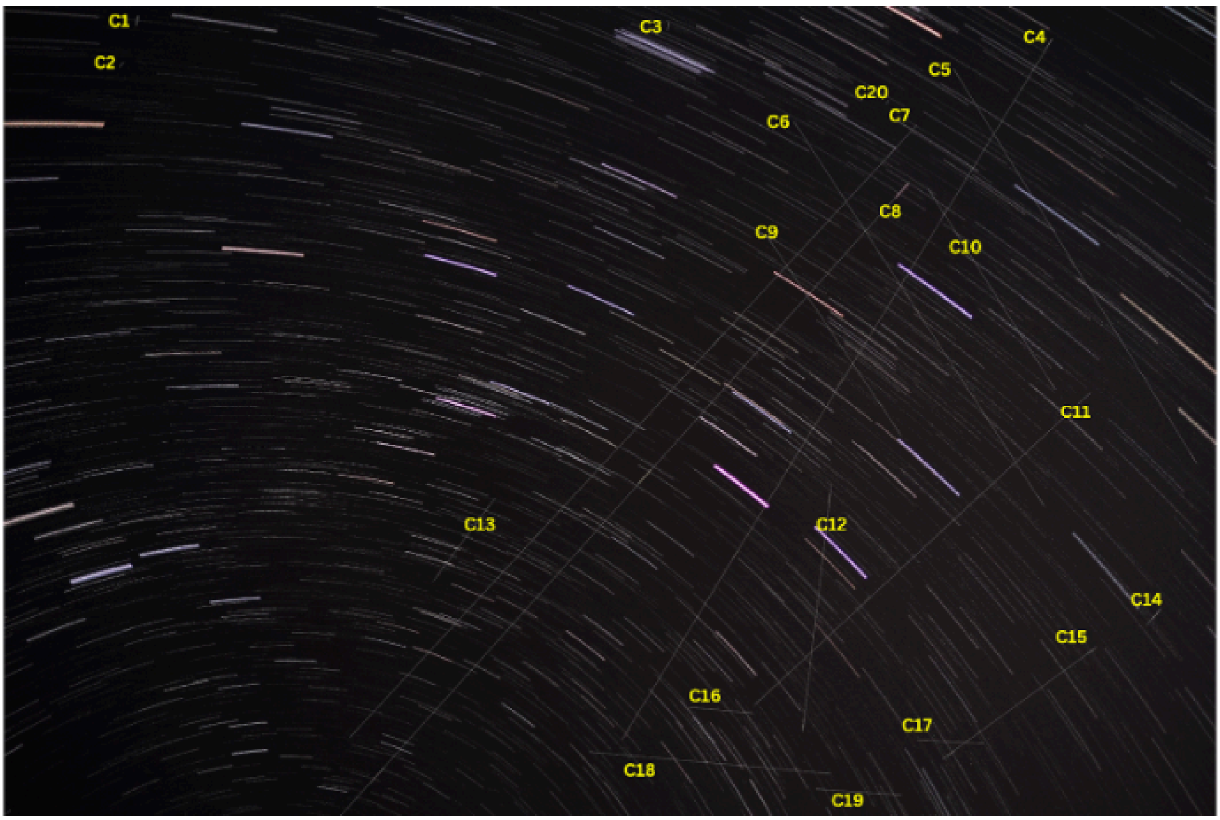
*Italics are trails that fit the debris profile.

Dataset B (February 26, 2024)

Candidate	Altitude (km)	Speed (km/h)	Photometric profile?	Identity
B1	916.29	26,663	Yes	Unknown

B2	524.97	27,411	No (too dim)	Starlink 4671
B3	576.81	27,309	No (too dim)	Starlink 2387
B4	781.24	26,914	No (too short)	Unknown

Dataset C (February 13, 2024)



Note: Trails in this dataset have been overlaid with translucent continuous lines to make them more apparent. See original image below table.

Candidate	Altitude (km)	Speed (km/h)	Identity
C1	514.73	27,432	Iridium 165
C2	795.595	26,887	Fengyun 3B
C3	649.66	27,166	Unknown
C4	782.59	26,912	Unknown
C5	563.28	27,335	Starlink 1038
C6	594.82	27,273	Unknown

C7	488.63	27,484	Unknown
C8	309.35	27,852	Unknown
C9	594.82	27,273	Unknown
C10	594.82	27,273	Unknown
C11	851.01	26,784	Unknown
C12	479.85	27,502	Unknown
C13	1063.1	26,398	Unknown
C14	485.662	27,490	Unknown
C15	782.59	26,912	Unknown
C16	655.12	27,155	Unknown
C17	655.12	27,155	Unknown
C18	568	27,326	Unknown
C19	534.35	27,393	Unknown
C20	842.96	26,799	Unknown

8. Appendix B (Codebase)

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8.1 Speed analysis code

```
import numpy as np
import matplotlib.pyplot as plt
from random import randint



# Defining constants and our model function
G = 6.67430e-11 # Gravitational constant (m^3 kg^-1 s^-2)
M = 5.972e24 # Mass of the Earth (kg)
altitudes = np.linspace(200, 400, 100000) # one million steps from 200 km to 400 km above sea level
speeds  = np.sqrt(G*M/((altitudes+6350)*1000))*3.6 # Model equation



# -------------------------------SECTION TO BE FILLED IN BY USER------------------------- #


# PUT PIXEL COORDINATES HERE (XXXX,YYYY e.g. 949, 677) FOR BOTH ENDS OF THE TRAIL. Order doesn't matter for xy1 and xy2
xy1_pixels = ????,????
xy2_pixels = ????,????
xy_uncertainty = ?,?  # Variation in pixel length in the x,y directions. 5,5 is a good estimate but you be the judge
```

```
transit_time = 1  # in seconds. The time it took for a trail to traverse the observed distance (i.e. shutter speed, 1 by default)

# INSERT IMAGE DIMENSIONS (????, ???? e.g. 1776, 1184)
dimensions = ????,????



# ------------------------------------------------------------------------------------- #

# Some really ugly calculations (mainly pythagoras' theorem and converting angular to linear speed) but, hey, it beats doing it by hand!
diag_dimensions = np.sqrt((dimensions[0])**2+(dimensions[1])**2)
diag_pixels = np.sqrt(np.abs(xy1_pixels[0] - xy2_pixels[0])**2+np.abs(xy1_pixels[1] - xy2_pixels[1])**2)
u_diag_pixels = np.sqrt(np.abs(xy_uncertainty[0])**2+np.abs(xy_uncertainty[1])**2)
rad = (108/diag_dimensions)*(diag_pixels)*(np.pi/180)/transit_time
u_rad = (108/diag_dimensions)*(u_diag_pixels)*(np.pi/180)/transit_time
print(f"Angular speed: {rad:.4g} +/- {u_rad:.3g} rad/s")
rad_model = rad*altitudes*3600
u_rad_model = u_rad*altitudes*3600


# Split a plot into two, one for the 95% confidence interval (fig) and the other for the model + data (ax)
fig, ax = plt.subplots(figsize=(7, 6))

# Add gridlines
ax.grid(which='major', color='#DDDDDD', linewidth=0.8) # Show the major grid
```

```
ax.grid(which='minor', color='#DDDDDD', linestyle=':', linewidth=0.5) # Show the minor grid as
well
ax.minorticks_on() # Make the minor ticks and gridlines show.

# Specify axes and title
plt.xlabel("Altitude (km)")  # x-axis label
plt.ylabel("Orbital speed (km/h)")  # y-axis label
plt.title("Predicted orbital speed by altitude") # Plot title

# Set intersection probe (idx) and define x, y intersection coordinates
idx = np.argwhere(np.diff(np.sign(rad_model - speeds))).flatten()
x_intersection = altitudes[idx]
y_intersection = speeds[idx]
print(f"Intersection: {y_intersection[0]:.5g} km/h at {x_intersection[0]:.5g} km above sea level")

# Plot the model and the CI
ax.plot(altitudes, speeds, color="blue", label=r"Minimum orbital speed model: $v =
\sqrt{\frac{GM}{R}}$") # Model plot
ax.plot(altitudes, rad_model, color="red", label=r"Projected speed of trail for different altitudes") #
Model plot
ax.fill_between(altitudes, (rad_model-(u_rad_model/rad_model)*altitudes),
(rad_model+(u_rad_model/rad_model)*altitudes), color='b', alpha=.1, label='95% Confidence
Interval') # 95% confidence interval region

# Plot the intersection points
plt.plot(x_intersection, y_intersection, 'ro', label="Intersection of speed model and projected trail
speed")
```

```
ax.axvline(x_intersection, color="g", ls='--', lw=1, label="Intersection axis") # Dashed vertical line denoting boundary between LEO/MEO

ax.legend(bbox_to_anchor=(1, 1), loc="upper left") # Specifying location of legend box where the image is (to its)"upper left"
plt.show()
```

—---

—----------------------

8.2 Database code

```
# Database code
import re
import sys
import time
import requests
import pandas as pd
from bs4 import BeautifulSoup
from selenium import webdriver
from selenium.webdriver.common.by import By
from selenium.webdriver.support.ui import WebDriverWait
from selenium.webdriver.support import expected_conditions as EC


# Get the date
date = input("Date (MM/DD): ").strip()
month, day = date.split("/")
```

```
regex_date = "^(0[1-9]|1[1,2])\/(0[1-9]|[12][0-9]|3[01])$" # Specifying expected format with "regular
expressions"
if not re.fullmatch(regex_date, date):
    sys.exit("Invalid date format.")



# Set observation period (24-hour time in hour:minute-hour:minute)
period = input("Observation period (e.g 18:30-20:15): ").strip()
start, end = period.split("-")
regex_time = "^(?:[01]\d|2[0-3]):[0-5]\d-(?:[01]\d|2[0-3]):[0-5]\d$"
if not re.fullmatch(regex_time, period):
    sys.exit("Invalid time format :(((")



# Convert to datetime format
start_date = pd.to_datetime(start)
end_date = pd.to_datetime(end)

# Get the URL
url =
f"https://in-the-sky.org/satpasses.php?day={day}&month={month}&year=2024&mag=5&anysat=v1
&group=44&s=&gs=gs&town=5814616"

# Find the location tag and make sure it's correct
r = requests.get(url)
soup = BeautifulSoup(r.content, 'lxml')
location = soup.find('div', class_='banner_txt_location')
```

```
location = location.get_text().strip()
print(f"Location: {location.replace('Location:', '').strip()}")
if "Vancouver" not in location:
    sys.exit("Incorrect location!")

print()
print("Launching browser...") # Don't click on any links on the webpage, let the library do its thing!

# Initialize the Selenium WebDriver (you can choose a different browser if needed)
driver = webdriver.Chrome() # webdriver.Firefox/Edge/Safari()

# Open the website
driver.get(url)

# A nice little touch ;)
print("Loading...")

# Wait for the table element to be visible, then fetch it (timeout in 45 seconds but adjust as needed)
wait = WebDriverWait(driver, 45)
table = wait.until(EC.visibility_of_element_located((By.CSS_SELECTOR, "div.sat_passes")))

# Read the table into a Pandas DataFrame
df = pd.read_html(table.get_attribute("outerHTML"))[0]

# Return table with time conditions
df = df.loc[(pd.to_datetime(df["Start"]["Time"], errors="coerce") < end_date) &
(pd.to_datetime(df["End"]["Time"], errors="coerce") > start_date)]
```

```
df = df[["Unnamed: 0_level_0", "Start", "Highest", "End"]]
df.reset_index(drop=True, inplace=True)

# Prettify the table with custom settings
pd.set_option('display.max_rows', None)
pd.set_option('display.max_columns', None)
pd.set_option('display.width', 1000)
pd.set_option('display.colheader_justify', 'center')

# Indicate dimensions
print("-"*21)
print(f"{df.shape[0]} rows x {df.shape[1]} columns")
print("-"*21)

# Print the DataFrame!
display(df)

# Close the browser
driver.quit()
```
—---

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Dear Editor,

Concerning our T2 project report, questions that were raised during the peer-review process have been addressed below. These questions have been included at the end of the letter for your reference.

Commenter #1 has raised an important point regarding the limitations of the equipment in use, namely the Fujifilm X-T3 camera. However, the use of a camera for this project is in fact the premise of the entire study. It is true that the Fujifilm X-T3 model itself is not explicitly used for astrophotography of this sort yet, to our knowledge, the camera's specifications posed no challenges to the data collection regime. If any technical barriers were encountered during data collection, they were highlighted in the discussion and, to a lesser extent, the methodology sections of the report.

C**ommenter #2** recommended we structure some sections of the methodology under subheadings. This was a very welcome suggestion which we have implemented throughout the paper and not just the methodology.

Commenter #3 advised rectifying some styling errors, such as a dangling asterisk and sectional word counts. These issues were promptly addressed and we thank the commenter for their eye for detail.

Commenter #4 emphasized an excellent point regarding previous research and literature on this topic. Indeed, various journals have been consulted that contain extensive research on orbital dynamics on this point. Unfortunately, there is scarce data on the use of cameras in ground-based space surveillance systems. We hope to alleviate that with the publication of our research report, setting the stage for thrifty science vis-a-vis space debris tracking.

Commenter #5 gave exceedingly helpful feedback on the structural and stylistic components of our paper. We have implemented many of their suggestions, such as the order of content, presentation, sentence clarity, and the content of our appendix. Their contributions are very much appreciated.

Commenter #6 had no qualms with our paper and was very encouraging of our progress. We thank them for their kind words.

Commenter #7 highlighted crucial aspects of the weather that needed to be taken into consideration during the data analysis. In particular, cloudy conditions and (implicitly) the presence of significant background light pollution pose significant challenges to space debris detection and photometric profiling. We discussed this near the end of the paper and have commented on the effect on the results of the study.

Commenter #8 stressed the importance of concision, readability and a logical structure. We have taken much of this advice to heart, attaching much importance to the flow of the paper, the quality of the information presented and the use of accessible language for a non-expert audience. They have also underscored key elements of a discussion section, such as the limitations in the study, possible improvements and areas of further research, which we have all taken into account. For this, we thank them and all the other commenters once more for their superb advice and/or words of encouragement.

There being no further concerns, the article has been jointly submitted with this letter for publication.

Sincerely,
Abdullah Bajaber and Emily Lau

Peer-review feedback

Commenter #1 –

“Every thing written so far felt very fuid and well reaserched as well as very intruguing. The backgroug information given was easy to understand and didn't leave me with any gaps. The organizing of your proposed sections makes sense logically. Your resoning for how you took and eliminted different data sets was well thought out. I can only say positive things for what was included in the report at this point in time due to the lack of other sections which haven't been completed. I can suggest to talk about some limitations the camera you used presented based on your personal experience using it.”

Commenter #2 –

- “Composition
  - How the report is structured and organized (logical flow?)
    - I love the use of pictures within the report as it helps guide the reader throughout the experiment
    - There is still some sections that have to be completed, but based on what is already done, the composition including the structure and organization is concise and easy to follow along, great work!
- Project Design
  - Assesses the planning and methodology used in carrying out the project or research
    - I liked the mention of specific camera settings used, as it makes it very helpful for others who may try and redo or further extend the research
    - I liked the mentioning of the 2 methods used; as a suggestion, maybe make a sub section for each of the methods to emphasize the different procedure carried out. Great work!
  - Does the research project demonstrate careful consideration of variables, data collection methods, and potential limitations.
    - The uncertainty in measurements is still something listed under “incomplete sections” and I assume that the limitations and consideration of variables are going to be mentioned within the discussion, which is still to be completed,

but if it is done within the same attention to detail as was paid for the methodology, it should be great :)

        - There was significant information made about the assumptions within this experiment which I thought was very helpful, and were all linked back to their significance in the research, and why it was important to make those assumptions. Great work!

- Interpretation
    - Is the analysis done correctly?
        - The results section is still to be completed, along with the analysis
    - Do they make logical inferences?
        - I am assuming there are going to be more logical references made within the extension of the discussion, but there was considerable information within the mention of assumptions that pertained to logical inferences about the theory present in the research. Good work!!
- Context
    - Is there enough context to help readers understand why the research is important
        - Again, I am going to assume there is going to be more information given about the significance of the research, but there is a great amount mentioned in the introduction.
        - The introduction was my favourite so far as it really emphasized the importance of the research! I found i tremendously interesting and I hope to read the full report soon!!

Overall great work!! I found this project to be extremely interesting and I am really excited to see the finished result!"

Commenter #3 –

"Overall Feedback

- Consider removing the word count on the individual sections; I don't think it will add anything to the report (except extra words :).

- Abstract: I absolutely loved your abstract! It caught my attention right off the bat and was very informative about your project. I especially liked how flowery your writing is and I could tell you definitely are a great writer. Consider adding in a small sentence or two about the findings of your experiment.

- Introduction: Was very well referenced and informative. A little confused about why there was an asterisk behind "artificial satellites" in the first sentence, but not too big of a deal. For figure 1 caption, consider adding in what the data show and a general conclusion (is the space debris increasing exponentially? Linearily? How are the number of objects measured?Why is ther such a large increase in 2007?) Consider adding specific information about how the debris can affect people's daily lives, it will make it catch even more people's attentions.

- Methodology: I loved how specific you were about the settings of the camera and the conditions the experiments were conducted in. This ensures reproducibility of your experiment and really adds to the sophistication of the experiment.

- Results: Spectacular analysis and reasoning for the assumptions. Best of luck completing the rest of your analysis :) For the figure 2 caption, please explain more about the figure. It should include all the components mentioned in Shania's class: the methods, experimental setup, results, etc.

Composition

- The report is structured very smoothly and is easy to follow along. The writing was also very colourful and made it a lot more appealing to read :) Although some parts are missing, I look forward to seeing what the final report looks like! I especially like how thorough you were with the word limits, but avoid including the word count in the final submission.

Project Design

- The planning and methodology was very thorough and showed an intricate understanding of the environmental factors that may affect your results. Steps were taken to mitigate these factors; great work!

- Although you did mention many assumptions that make it easier for you to analyze the data, consider also talking about potential limitations (ie will the time of year affect anything, will the weather affect the visibility of debris far away from the surface?).

Interpretation

- The analysis and logical inferences is incomplete as of right now, but given how the current report is turning out, I have no doubt it will be amazing :)

Context

- There is a perfect amount of context to help readers understand why this is important to them in addition to what the current research is about.

Conclusion

Congratulations, this was one of the best reports I have read and no doubt the easiest to read. Your language choice, grammar, and sophistication was impeccable. There were small edits that may need to be done (above), but once those are done, your report is ready to go! I look forward to seeing your presentation at Loon Lake!"

Commenter #4 –

"Hi Emily and Abdullah!

I want to start off by saying that even though I'm not a physics person, you're research topic is very intriguing!

By reading the introduction, I was able to fully grasp why your research, which is about having an alternative approach for detecting large debris fragements, is significant to reserach about. One thing I can suggest is that even though your research may be the first to use the Fujifilm X-T3 for detecting orbital debris, I think it would be good to include previous research done by other scientists on detecting orbtial debris to discuss the limitations in your reserach and to also show how your research contributes to the scientific community.

In terms of your methodology section, it is very detailed and would allow other scientists to replicate your research. However, one suggestion I can give is to make subheadings for your methodology section. For instance, since you state that you have two primary methods to collect datasets for your study, you create subheadings for that (i.e (i) Method 1, (ii) Method 2). This would make your methodology section more easy to follow for the readers.

For your discussion section, I liked how you discussed assumptions and factors that could have made the results less valid. If the results section is complete I think it would be easier to comprehend the analysis you made.

Good work :)"

Commenter #5 –

“The report is well organized. I added some comments in the actual document, but they were all mainly small clarifications/structural errors. Assumptions and inferences were well stated. Good context given -- really helps address the importance of knowing about excess space debris and the consequences of such.”

Commenter #6 –

“So far the paper seems well written. The method section was very easy to understand and provided sufficient information for me to be able to understand how data was taken. The introduction did a good job of explaining the significance of this study. Not much to comment on right now but overall looks really good.”

Commenter #7 –

“Interesting topic! Good use of sources and explanation of method. I see little that you have not elaborated on, any questions I generated were answered in the following paragraph.

Is there anything else that could have affected the results ehrn data was taken? Would clouds have an effect on visibility or is there a way to determine if the sky is clear enough to take data?”

Commenter #8 –

“A very good report overall. Although it is not finished, I feel really confident in the rationale behind the study and very interested on your findings. Since it is not yet finished, it is hard for me to provide any feedback, but the written portions are very well-written and detailed. My only tip would be to provide the methods with more organization like headlines to make it easier for the reader to pinpoint the parts of the method they need to read. Additionally, the methods is a bit lengthy, which is not neccesarily bad, but it could defineitly be more concise. Overall, I am very interested in the final report. The rest is missing, but I can add some feedback that I've left for other people. I think usually what is missing is a summary of results, justification of uncertainty, and consice-ness. You want your writing, especially the discussion, to flow well so don't forget to present your findings in a logical order. If you plan on sumarizing your results and also intepreting statistical significance or whatever the data analysis will be, try to keep the summary before the analysis so the reader can follow it more easily. For discussion, don't forget to include limitations, improvements, and further studies that could investiagte your topic. I hope this helps.”