Modeling Orbital Debris Density in Low Earth Orbit

Final Report

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Summary of research questions

1. **Is the amount of orbital debris in LEO increasing?** Yes, orbital debris is accumulating over the years. The trend has been steady, with the occasional spike, but in recent years has experienced a slight parabolic increase in orbital debris accumulation over time.

2. **If the amount of orbital debris in LEO is increasing, will that increase result in manned spaceflight becoming unsafe to continue**? As the amount of debris increases, the chances of a spacecraft colliding with the debris increases. However, we were not able to determine a cutoff for safe space flight. The definition and equations used to determine unsafe spaceflight was found to be flawed. The proper method of answering this question is much too complex given our current skill levels.

3. **Do the other Earth orbits (MEO, GEO, and HEO) experience similar increases in orbital debris?** Yes, all earth orbits experience similar trends in the accumulation of orbital debris. As the altitude increases, the amount of debris in these orbits decreases in quantity, but all regions in earth orbit experience a positive increase in orbital debris over time.

Motivation and background

This project examined the impact of orbital debris in Low Earth Orbit (LEO) on the future of space flight. Orbital debris is man-made material from spacecraft that is no longer serving a purpose but is still in orbit (The Aerospace Corporation, 2018). It includes obsolete spacecraft, tools such as pliers, and rocket parts. This orbital debris can collide with spacecraft, causing serious damage. A large amount of orbital debris leads to a higher chance of collision for a spacecraft. In creating their collision avoidance system, the European Space Agency considers a chance of collision greater than 1 in 10,000 to require a collision avoidance maneuver (2019). We attempted to use this probability of collision to determine the cutoff for safe manned space flight. An inability to conduct manned spaceflight would limit further space exploration.

Dataset

The dataset used for this project is from Space-Track.org. Data is obtained by the U.S. Space Surveillance Network (SSN), which is then analyzed and compiled by the 18th Space Control Squadron. It requires a free account to view. After making an account, you will receive an email to verify your account that includes a link to set your password. Data from this website is updated frequently and can be downloaded as .txt files in the Two Line Element (TLE) format. Each piece of debris is condensed into two lines of data. The first line has basic object information, such as the satellite catalog number and the international designator. The second contains orbit information, such as, orbit inclination, eccentricity, and the argument of perigee (Space-track.org, 2020). The data we used is from 2020.
https://www.space-track.org/basicspacedata/query/class/tle_latest/ORDINAL/1/EPOCH/%3Enow-30/orderby/NORAD_CAT_ID/format/tle

Methodology

Data Processing

Orbital debris data was accessed from Space-Track.org as a text file and processed into a CSV file. Each line in the CSV file represented a different piece of orbital debris, containing data for that object. This allowed us to calculate additional information about each piece, such as altitude and probability of impact, before grouping and sorting the objects.

Calculating Probability

For probability calculations, we utilized the following equation for collision probability, found in Valsecchi et al.,, $P = \frac{U}{(2*\pi^2\, a^{1.5}\, |U_x|\, \sin(i))}$. Units are in $m^{-2}\, year^{-1}$, and U and U_x

are the debris' relative velocity to the target (our satellite), and the velocity's component along the axis containing the center of Earth's mass and the satellite's position, respectively (Valsecchi, 2000)

$$U = \sqrt{3 - \frac{a_0}{a} - 2\sqrt{\frac{a(1-e^2)}{a_0}}\cos(i)}$$

$$U_x = \pm\sqrt{2 - \frac{a_0}{a} - \frac{a(1-e^2)}{a_0}}$$

For the purpose of this project, the newly launched satellite is assumed to have a circular orbit with an altitude of 300 km, which therefore means $a_0 = 300\ km$.

The other orbital parameters are for the piece of space debris or satellite already in orbit, where *i* is the orbital inclination, a is the semimajor axis, and e is the eccentricity of the orbit. These parameters can be found in our dataset. If we multiply P by the area of the target spacecraft (assumed to be 1 square meter), the probability per year is calculated. If the Probability returns NaN, then it can be assumed that the debris will not hit the target satellite, and as such will be filtered out using dropna(). After evaluating this expression for all satellites in orbit, we summed up the probabilities to get the total probability of collision.

Analysing Increase of Object Count and Probability

To find the amount of objects present each year, we sorted the objects by launch year. By calculating the sum of all the objects launched each year and every previous year, we found the total count or objects in the dataset that would have been in orbit for each year. Similarly, we could add the probabilities of impact with our target orbit for each object to find the total chances of impact for each year. To visualize the trends, we made graphs of the total probabilities and object counts over time. We then found polynomial lines of best fit: one for object count as a function of time, and another for probability of impact with the target orbit as a function of time. To evaluate the strength of these models, we used three strategies. The first was to overlay the model on a scatter plot of the data as a visual check for how well the model fits the data. The second was to calculate the R-squared value as a statistical measure of the model's fit. Finally, we plotted the residuals (calculated by subtracting the predicted values from the actual values) to assess the randomness of the model's errors.

Analysing Different Orbits and Altitudes

We used the four earth orbits that are defined by NASA: low Earth orbit (LEO), mid Earth orbit (MEO), geosynchronous orbit (GEO), and high Earth orbit (HEO). An object was defined to be within the orbit if its path crossed the orbit at any point, so that some objects may be counted as within multiple orbits. Boundaries for the orbits, in terms of altitudes, are: 2000 km or less is LEO, 2000 km to 35786 km is MEO, 35786 km is GEO, and above 35786 is HEO.

Calculating the altitudes from the information used the following equations (Valsecchi, 2000):

$$
\begin{aligned}
r_p &= a(1-e) \\
r_a &= 2a - r_p \\
z_p &= r_p - R \\
z_a &= r_a - R
\end{aligned}
$$

Were a is the semimajor axis in km, e is the eccentricity, R is the radius of the earth (6378 km), z_p is the altitude of the perigee (lowest point in the orbit), and z_a is the altitude of the apogee (highest point in the orbit).

Visualizations were used to compare the trend of orbital debris accumulation in different orbits, as well as to assess the relationship between launch year and altitude.

Using Poliastro for creating visualizations

We used the library Poliastro to create visualizations of the boundaries for each orbit to accompany the bar graphs showing data separated by orbit for added context.

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Results

Research Question #1

Is the amount of orbital debris in LEO increasing?

The processed orbital debris was filtered for data with a semimajor axis less than or equal to 2000 km altitude, the region of earth's orbit defined as LEO. The data was further filtered by year, with the total count of orbital debris for each year, starting in 1958 and ending in 2020, being tallied. A visual representation of this data is the clearest method to answering the research question. Figure 1 below is a bar chart showing both the total tally of orbital debris from the previous years in blue, as well as, the additional debris accumulated for the current year in orange. From this figure, it can be seen that the amount of orbital debris has increased from zero to over 16,000 currently tracked objects in Low Earth Orbit. Figure 2 is a line plot showing the count of orbital debris over time, a different representation of the same data. This shows a fairly consistent increase in orbital debris per year from 1958 until 1992. After some larger spikes in orbital debris accumulation from 1993 through 2001, the amount of orbital debris accumulating per year has slowed. Starting in 2017 however, the amount of debris accumulating per year has been on the rise.

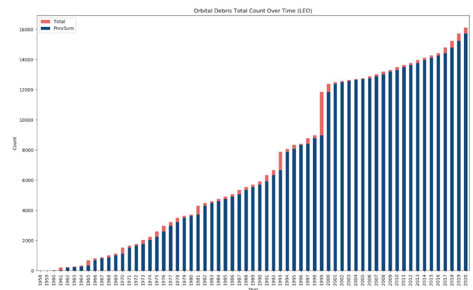

Figure 1.

Besides visual inspection, a polynomial model of the orbital debris over time was created to further analyze any possible trends. This polynomial model can be seen in Figure 3. It is a second order polynomial with positive coefficients. This shows a clear positive trend in the accumulation of order debris since the first spacecraft were launched in the 1950's. These three figures all show a clear and significant positive trend. Most surprisingly, there doesn't appear to be a negative slope in the data, i.e. there has never been more debris leaving orbit or burning up than new debris reaching orbit in LEO. With this in mind, it is realistic to predict that this trend will continue with a purely positive slope of orbital debris accumulation every year unless significant efforts are made to reduce the amount of orbital debris through man-made means. Our equation for polynomial fit for number of objects was (Figure 3):

$$1.363x^2 - 5133x + 4.826 \times 10^6$$

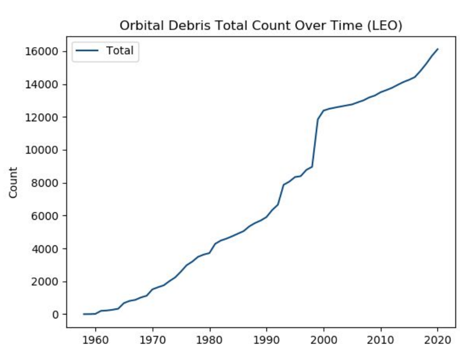

Figure 2.

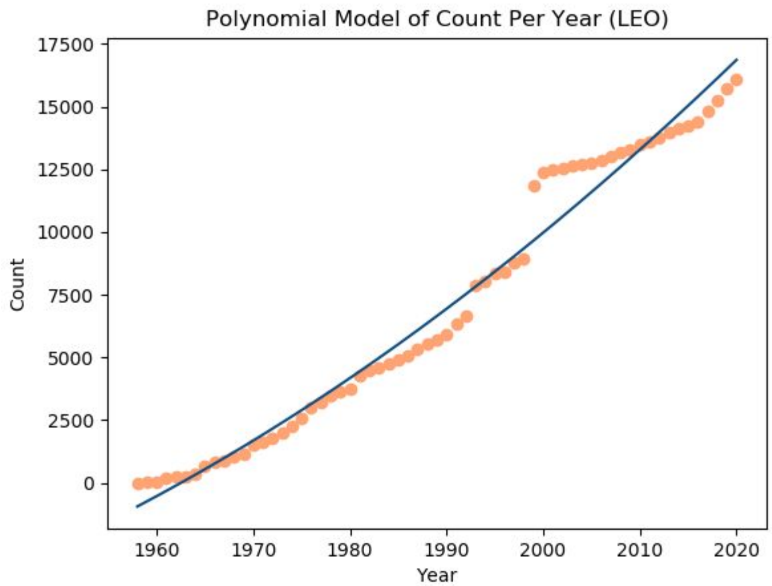

Figure 3

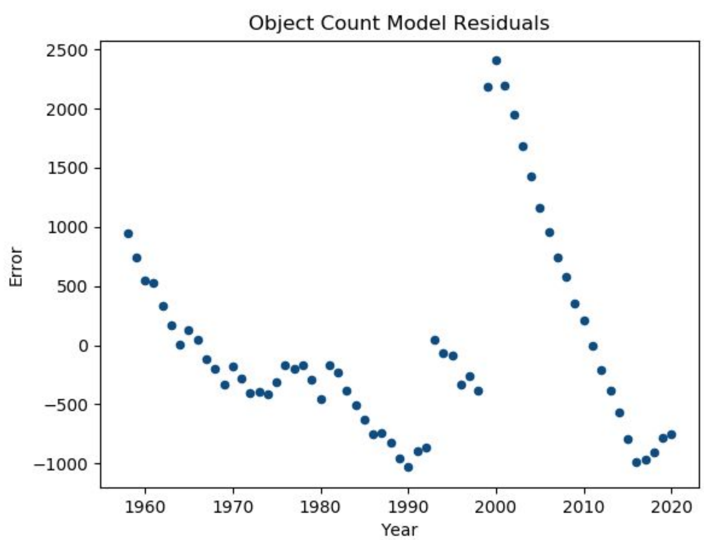

Figure 4

Our R-squared value was 0.976, indicating that 97.6% of the variation is explained by our model. However, the residual plot does not show independence, as the residuals form a pattern rather than being random. This indicates that our data is not a good candidate for polynomial regression.

Research Question #2

If the amount of orbital debris in LEO is increasing, will that increase result in manned spaceflight becoming unsafe to continue?

As the amount of debris increases, the chances of a spacecraft colliding with the debris increases. However, we were not able to determine a cutoff for safe space flight. Using our equations for probability, the cutoff was determined to occur in 1971, as shown in Fig. 5. This seems unrealistically early since there is a modern space station orbiting at our target orbit. This can be attributed to the flaws of our chosen model. To begin, this model only depended on the relative speeds of the projectiles, and not a velocity described as a vector. Nor did it depend on a time dependent position between the two, or other parameters such as the argument of perigee (essentially where the lowest altitude is in reference to the equator). The model utilized is likely an oversimplification for a case with only two bodies and assumptions such as shared arguments of perigee, and the target orbit being circular. A more accurate model would be one that is a time based function that includes a referenced starting point and all orbital parameters for both orbits.

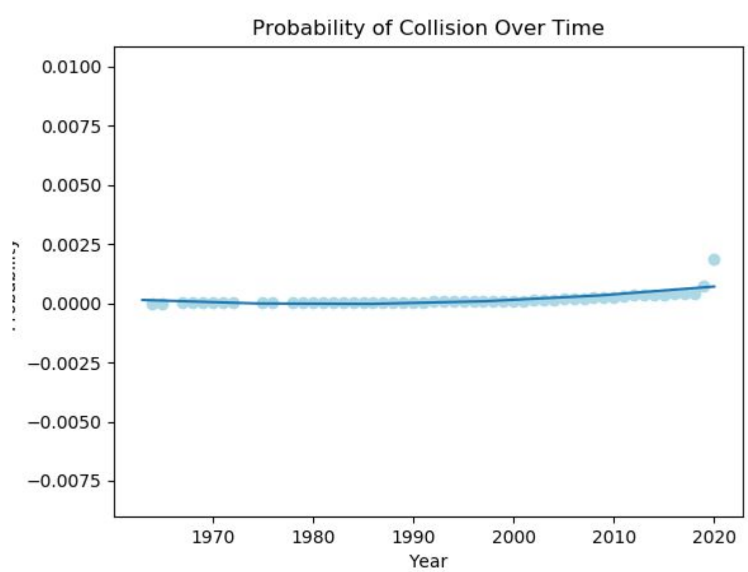

Figure 5.

Polynomial fit for probability equation was:

$$5.041 \times 10^{-7}x^2 - 0.001998x + 1.98$$

Our R-squared value was 0.594, indicating that only 59.4% of the variation is explained by our model. Also, the residual plot does not show independence, as the residuals form a pattern rather than being random. This indicates that our data is not a good candidate for polynomial regression.

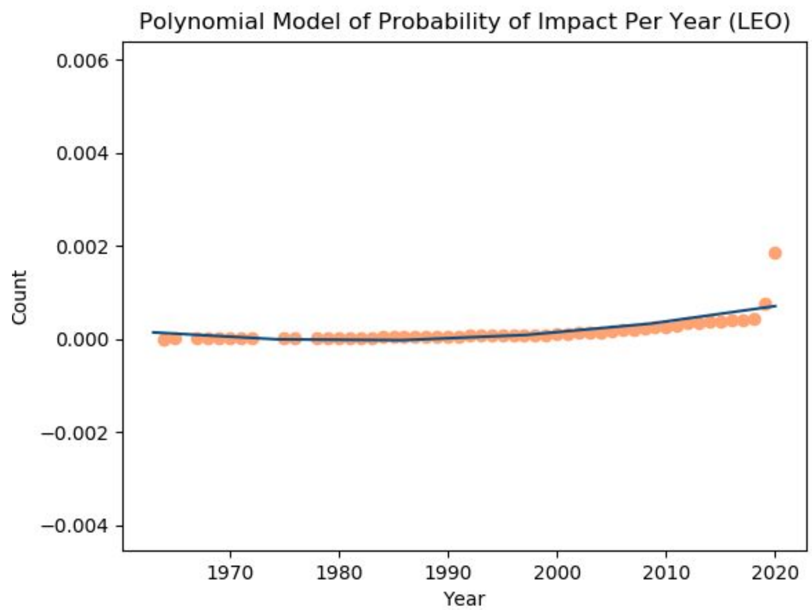

Figure 6.

Research Question #3

Do the other Earth orbits (MEO, GEO, and HEO) experience similar increases in orbital debris?

The same methodology used to answer Research Question #1 was used for this question. Earth orbit is separated into four regions; Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geosynchronous Orbit (GEO), and High Earth Orbit (HEO). LEO has an orbit greater than 150 km and less than or equal to 2000 km, MEO has an orbit greater than 2000 km and less than 35,780 km, GEO has an orbit at 35,780 km, and HEO has an orbit greater than 35,780 km (Riebeek, 2009). A visual representation of these earth satellite orbits can be seen below in Figure 7.

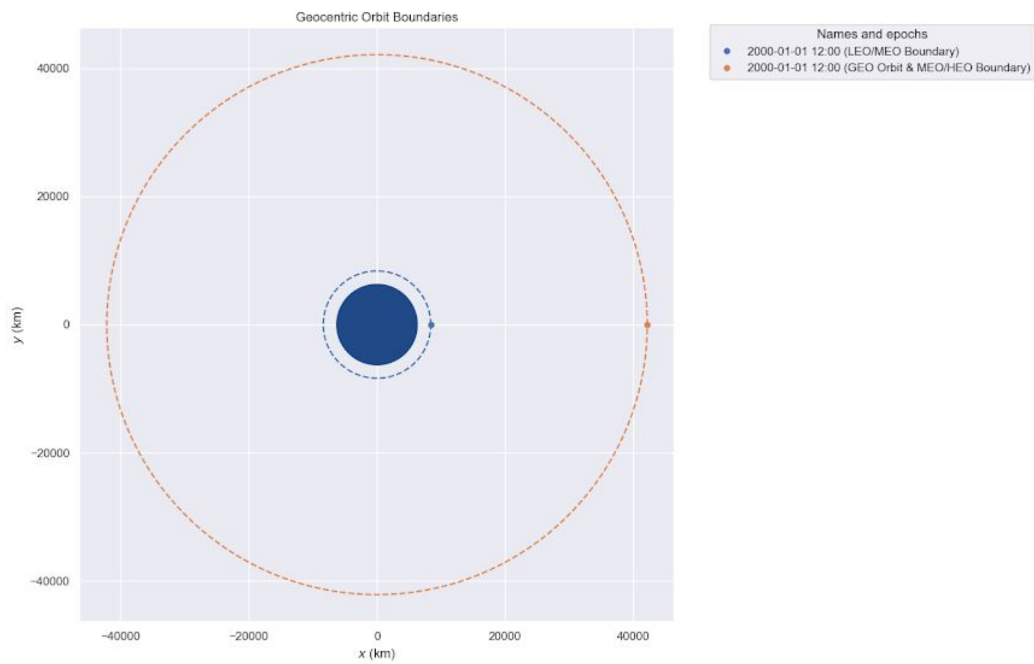

Figure 7.

In order to determine the accumulation of orbital debris over time in all of the regions in earth orbit, multiple visual representations were used. The first figure you can find below, Figure 8, shows the total amount of orbital debris every year broken up by earth orbit. This figure shows the same trend as in Figure 1, but with a more pronounced slope starting in the year 1999. The amount of orbital debris appears to be trending in a parabolic shape and increasing in all regions of space. Figure 9 breaks these regions up and shows the amount of orbital debris accumulation over time. The trends in each region are similar, although as the altitudes increase, the amount of orbital debris is lower comparatively.

The amount of debris in LEO and MEO are the most and have the largest slopes, which is reasonable given all first stage pieces of rockets separate in LEO, and upper stage propulsion systems that place satellites into higher orbits will either separate from their payloads in LEO or MEO. Most communications, weather and spy satellites tend to be in

GEO, meaning that the propulsion stages that place them there will be below GEO. Since this area of space consists of government and key infrastructure pieces of equipment, it makes sense that there is less debris in this part of orbit. The orbital debris in HEO mainly consists of satellites that have reached the end of their lifespan. Current U.S. guidelines require satellites at the end of their lifetimes to be placed into a “graveyard” orbit at approximately 36,000 km above the earth (NOAA, 2016). This explains the higher rise and higher total amount of orbital debris in HEO compared to GEO.

These figures show the trends in orbital debris accumulation in other orbits besides LEO to be similar. Over time, the amount of space debris in all orbits around earth has increased, with LEO having the largest amount of debris.

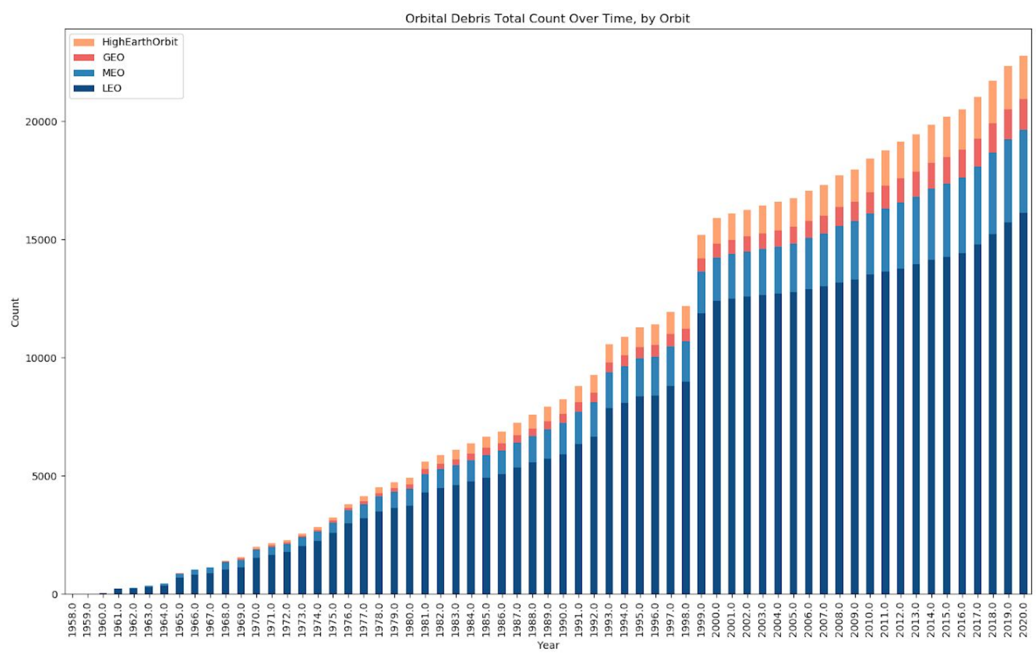

Figure 8.

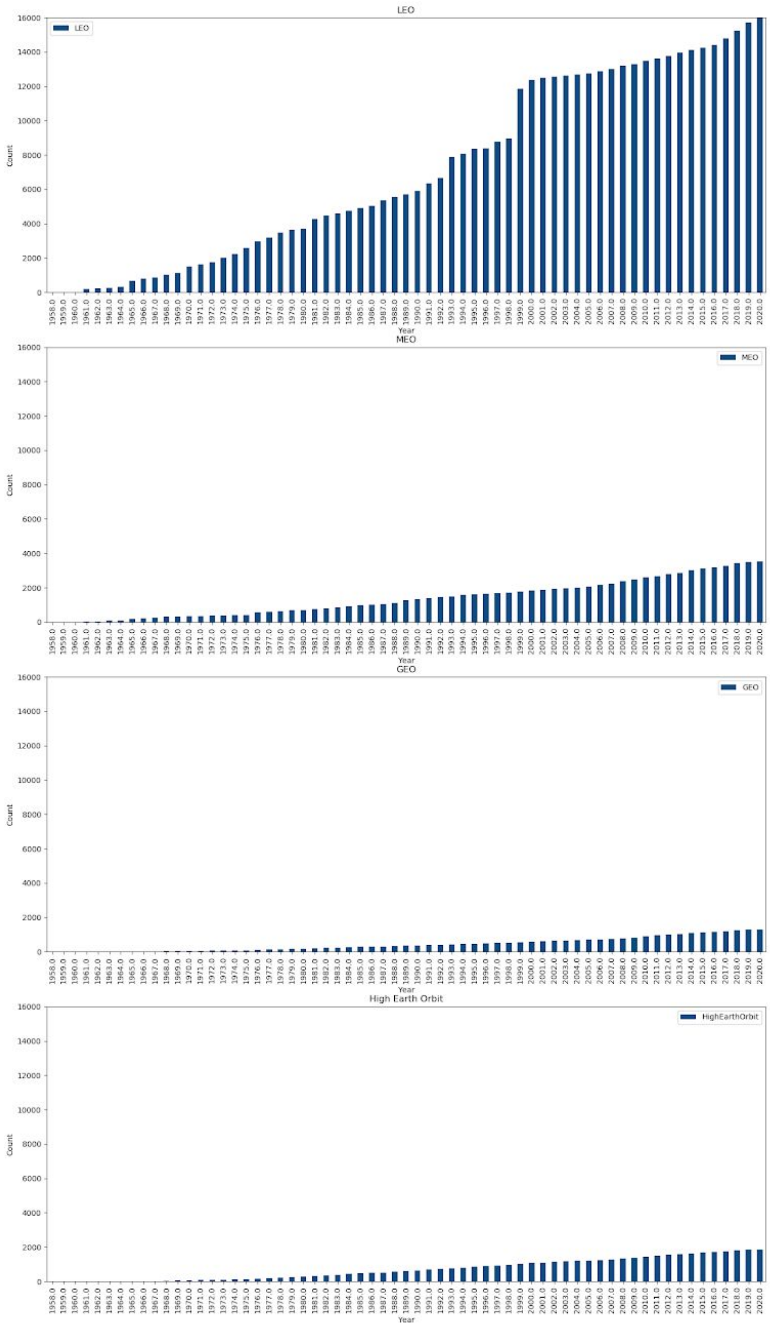

Figure 9.

Challenge Goals

Messy Data: The data was originally in a text file that had to be processed into a CSV file. Since it was in a two line element format, there was an added layer of complexity since data from two lines in the text file was sent to one line in our CSV. Secondly, the data in the text file couldn't be split by whitespace since some values were not separated by whitespace. Some values had assumed decimal points or other odd formatting that needed to be adjusted for our analysis.

We originally intended to use the API to gather more data, however we felt that it would have become a much larger project than felt feasible in the timeframe we had.

New Python Libraries: We used Poliastro for data visualizations. This included learning how to install a library and read the documentation.

Work Plan Evaluation

Tasks

1. Process the data into a pandas dataframe - Estimate: **30 hours**

   I think this took me about five hours total, so this was a bad estimate.

2. Find probability of collision for each year - Estimate: **5 hours**

Approximately 2 hours of work, most time was spent debugging calculation errors.

3. Create plots to visualize trends over time - Estimate: **5 hours**

   This probably took around 20 hours, given that the data sorting required was somewhat involved. I also found that I needed to figure out some plotting techniques that we hadn't covered in class.

4. Create model to project future levels & compute year at which we reach unsafe level - Estimate: **7 hours**

Creating the model took around 2 hours, most of which was researching possible methods for a polynomial line of best fit. The second part turned out not to be feasible.

5. Report & Slides -Estimate: **3-4 hours**

   The report took around three hours.

Testing

We used the asserts function from the homework to test our data analysis and calculations. We also used smaller files to run the tests on. For the data visualizations, we manually checked that the maximum and minimum values on the graphs agreed with the visualizations. Finally we had each other double check the code we had written individually.

Collaboration

Online Resources:

For polynomial regression with Numpy:
https://www.w3schools.com/python/python_ml_polynomial_regression.asp

Link to website with data: https://www.space-track.org/
(Account creation required, after doing so navigate to
https://www.space-track.org/basicspacedata/query/class/tle_latest/ORDINAL/1/EPOCH/%3Enow-30/orderby/NORAD_CAT_ID/format/tle)

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