Transdisciplinary Engineering Analysis of Orbital Debris

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ABSTRACT

Orbital debris growth is an ongoing hazard to satellites while also adding to the cost of operating satellites. In this paper, we present a data-analytics-driven model that incorporates exponential increase (supported by latest data) in space launches to predict orbital debris growth. Findings from our literature review allowed us to assemble data regarding orbital debris in Low Earth Orbit, and identify the risks posed by orbital debris to commercial, defense, and human exploration missions in space. The NASA ORDEM orbital debris tool was used to construct a nominal dataset to understand orbital debris versus time in various orbital belts focused on low earth orbit. Our analysis of the data revealed that particle sizes between 1 cm and 10 cm are the most critical as they are difficult to shield against and track in this range. Our initial model used the ORDEM-based data versus time curves to predict future debris. A key shortcoming of this type of model is that it is based exclusively on time-based data for prediction. As a result, this type of model vastly underpredicts future orbital debris. To ameliorate this problem, we gathered and analyzed FAA data on historical launch trends and discovered that this growth is in fact exponential. Equipped with this finding, we developed a more accurate model to predict future launches. We then incorporate this model along with the ORDEM dataset to better predict future orbital debris growth. On the basis of our research, we concluded that the onset of the Kessler Syndrome of runaway orbital debris growth in low earth orbit belts poses a near-term risk that needs to be addressed with urgency (12).

INTRODUCTION

The growth of the commercial launch industry, which has been exponential, is expected to continue this trend. For example, SpaceX alone accounted for over 100 launches in 2023. The growth in SpaceX commercial launch is illustrated in Figure 1.

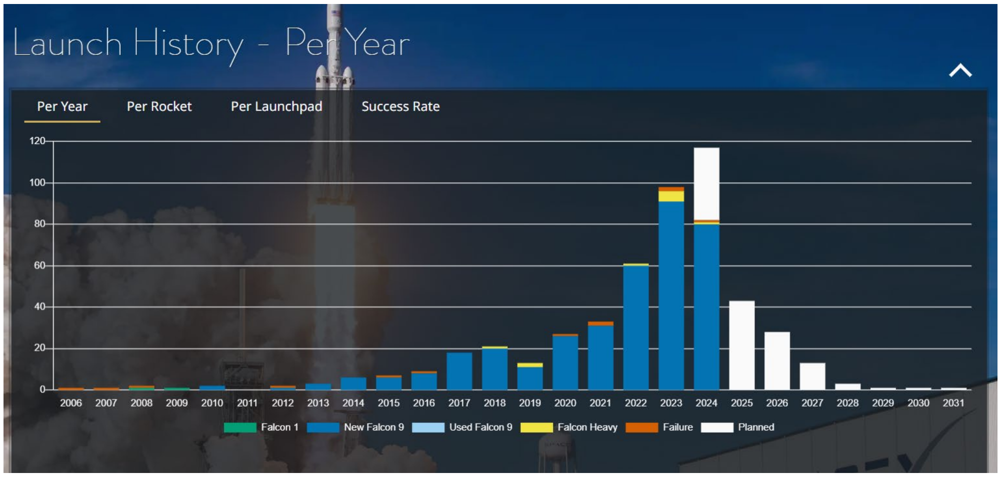


Figure 1. Launch History of SpaceX showing rapid growth (1)

Orbital debris is an ongoing threat that is expected to grow with the increase in space launches. It poses both a technical and economic challenge to successful mission accomplishment. This challenge is rooted in spacecraft resilience and the economic viability of future space missions. For manned spaceflight, orbital debris also poses a human safety risk, particularly in the context of Low Earth Orbit (LEO) missions under 2,000 km.

This paper presents a data-driven model to analyze orbital debris growth and specifically answer the following two questions:

- Given a growth rate of launch activity how much debris will exist in 5 years and beyond?
- What are the key parameters that will drive this growth – and how could it be mitigated?

Our research focus was on objects between 1 cm and 10 cm in size in the Low Earth Orbit (LEO) altitude region. Figure 2 depicts this by highlighting that for objects less than 1 cm, a space pressure vessel can be effectively shielded. For objects more than 10 cm in size, in-flight and ground tracking systems can mitigate the risk of collision.

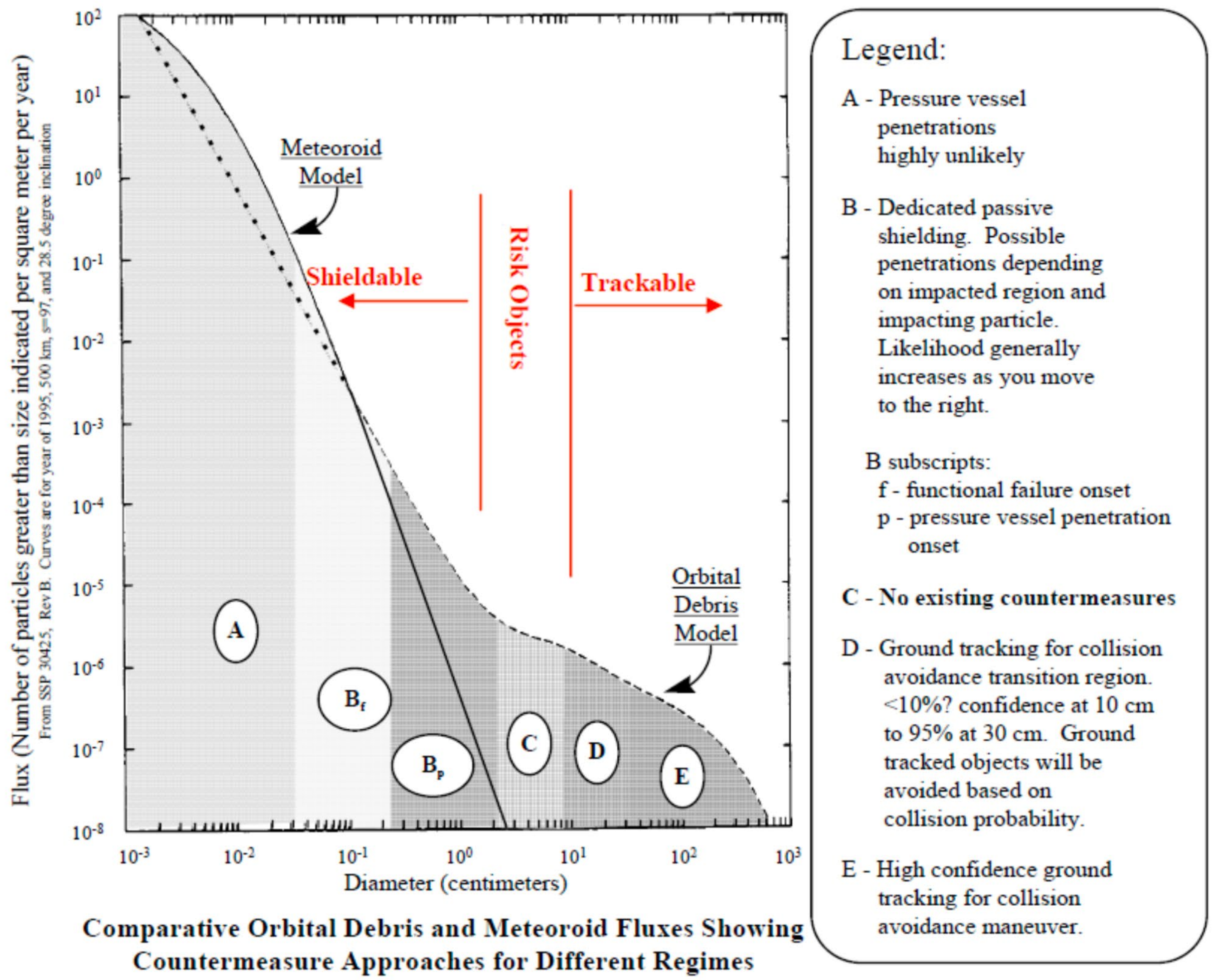


Figure 2. Orbital Debris Flux vs. Diameter (2)

QUANTIFYING SPACE DEBRIS

Space debris can be classified into three groups: (1) debris that arise as a necessary byproduct of missions (e.g., rocket stages), (2) debris generated by accident or oversight, and (3) debris objects resulting from intentional actions such as anti-satellite weapons (ASAT) tests (3).

When quantifying debris objects, the energy upon impact is found to be significant as shown in Table 1. The information on the former comes primarily from the US Space Surveillance Network.

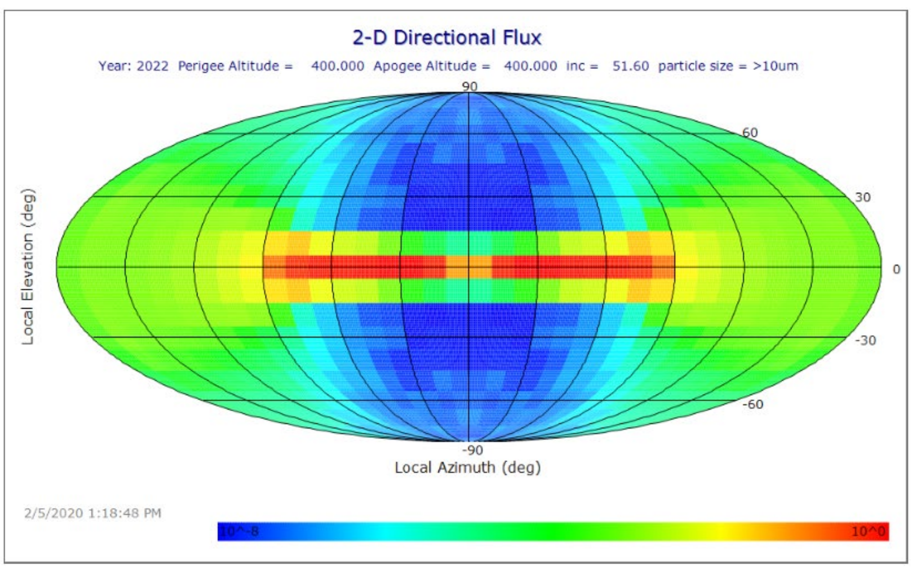
Table 1. Quantifying Orbital Debris Energy and Impact (4)

Debris Size	Similar in size to	Mass (g) aluminum sphere	Kinetic Energy (J)	Equiv. TNT (kg)	Energy similar to	Quantity	Trackable
1 mm	medium-grit sand or poppy seeds	0.0014	71	0.0003	Pitched baseball	Tens of millions	Can't be tracked
3 mm	smaller than BBs	0.038	1910	0.008	Bullets	Millions	Can't be tracked
1 cm	blueberries	1.41	70700	0.3	Falling anvil	Hundreds of thousands	Can't be tracked
5 cm	plum	176.7	8840000	37	Hit by bus	Tens of thousands	Most can't be tracked
10 cm	softball	1413.7	70700000	300	Large bomb	Tens of thousands	Most can be tracked
> 10 cm	basketball to football field	1400 to 500,000,000	Up to 1x10^13	Up to 3,000,000	Very large bomb	Thousands	Tracked and cataloged by the space surveillance network

It is important to note that particles between 1 cm and 10 cm pose a serious threat because particles of this size typically cannot be tracked.

TRANSDISCIPLINARY DATA- AND MODEL-DRIVEN ANALYSIS

For our analysis, we employed the NASA ORDEM 3.2 model and database to assemble a dataset from 2016 to 2024 at an apogee of zero degrees and an azimuth and elevation both set at zero degrees. The goal was a nominal dataset representative of orbital debris focused on Low Earth Orbit (LEO). An illustrative visualization of the ORDEM model is shown in the figure below.



ORDEM 3-dimensional average cross-sectional area flux for a spacecraft assessment, mapped to a 2-D directional flux projection. Hot colors indiciate areas of high flux while cool colors are areas of low flux. Direction relative to the spacecraft is noted in coordinates (local azimuth & elevation), where azimuth runs along the horizontal from left to right and ranges from -180° to 180° and elevation runs vertically from bottom to top and ranges from -90° to 90°. Credit: NASA ODPO.

Figure 3. Illustrative Visualization of ORDEM Model (5)

Table 2 shows an illustrative download from ORDEM for 2016.

Table 2. Illustrative Download from ORDEM (5)

ORDEM 3.2.0: ORDEM Telescope/Radar Mode							
Surface Area Debris Flux (#/m^2/yr)							
Year: 2016 Sensor lat. = 0.000 Pointing AZ = 0.000 Pointing EL = 0.000							
		Debris Size					
Alt	Rng	>10um	>100um	>1mm	>1cm	>10cm	>1m
200	1609.7	3.38E+02	6.64E-01	3.83E-03	1.52E-06	5.29E-08	2.62E-08
300	1979.1	3.38E+02	6.64E-01	3.83E-03	1.52E-06	5.29E-08	2.62E-08
400	2294	7.74E+02	1.94E+00	9.60E-03	2.70E-06	1.19E-07	6.42E-08
500	2574.5	1.92E+03	5.55E+00	1.92E-02	3.79E-06	3.34E-07	1.87E-07

Figure 4a shows the flux, which is proportional to the probability of impacting the debris, versus LEO altitude for the year 2023 and illustrates where the debris belts are concentrated.

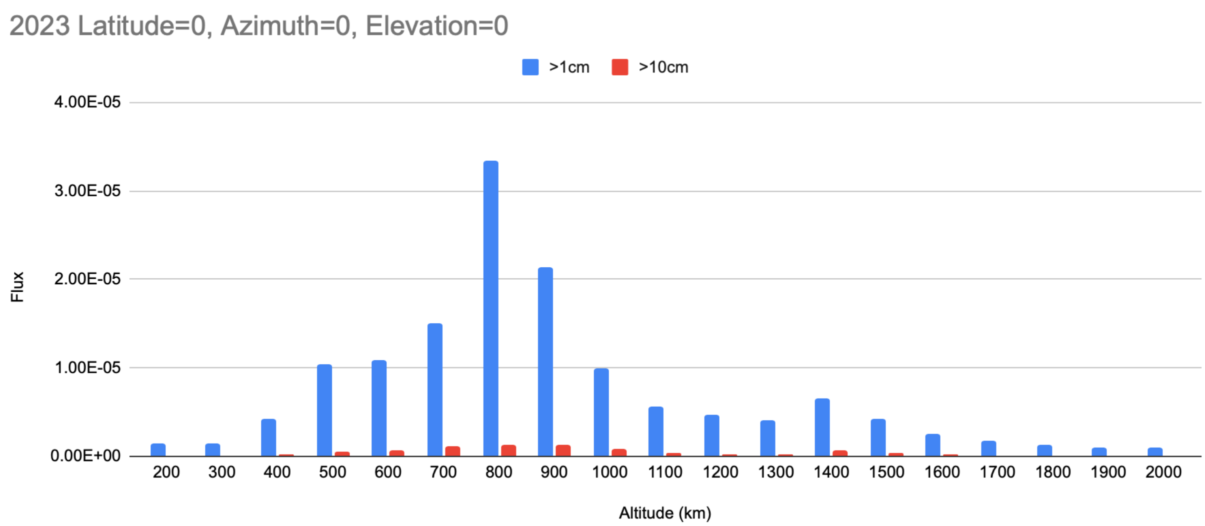


Figure 4a. Flux Distribution, Lat=0, Az=0, El=0

Importantly, the probability of impacting debris >10 cm is orders of magnitude lower than impacting debris >1 cm and as mentioned earlier the larger debris can effectively be tracked and avoided. In addition, the belt at 800 km has the highest orbital flux and thus the highest probability of collision with debris. It is interesting to analyze ORDEM data for Latitude=42.6 deg, Azimuth=90 deg, and Elevation=75 deg to investigate a similar flux pattern and this is shown in Figure 4b below.

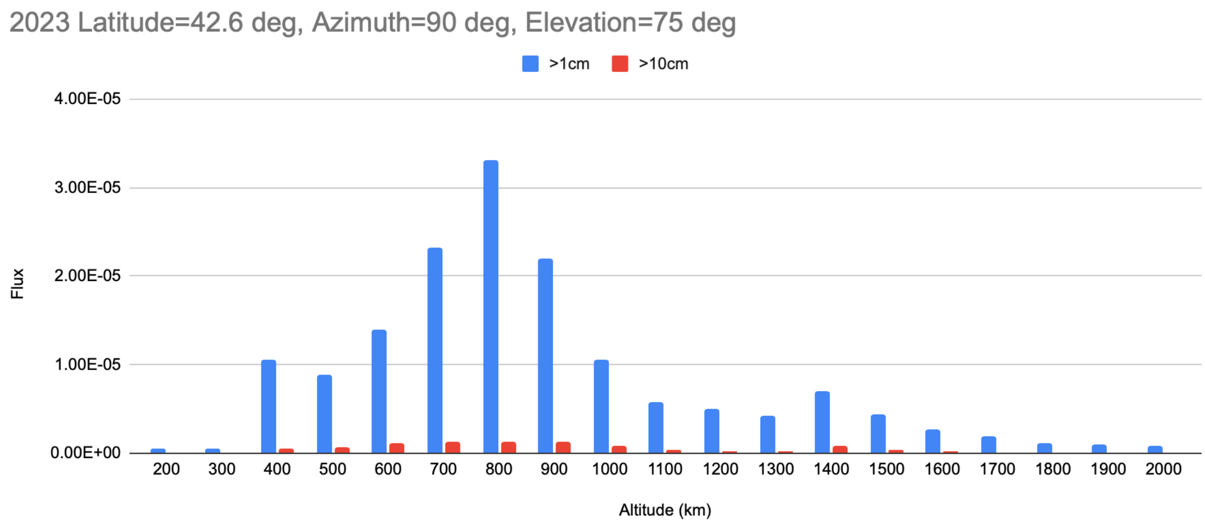


Figure 4b. Flux Distribution, Lat=42.6, Az=90, El=75

Here again the orbital belt at 800 km has the highest flux thus making this particular orbital altitude at a high risk of an orbital debris collision.

To visualize a representative time series, Figure 5 shows the debris flux >1 cm at 1100 km and 800 km for the years 2016-2024.

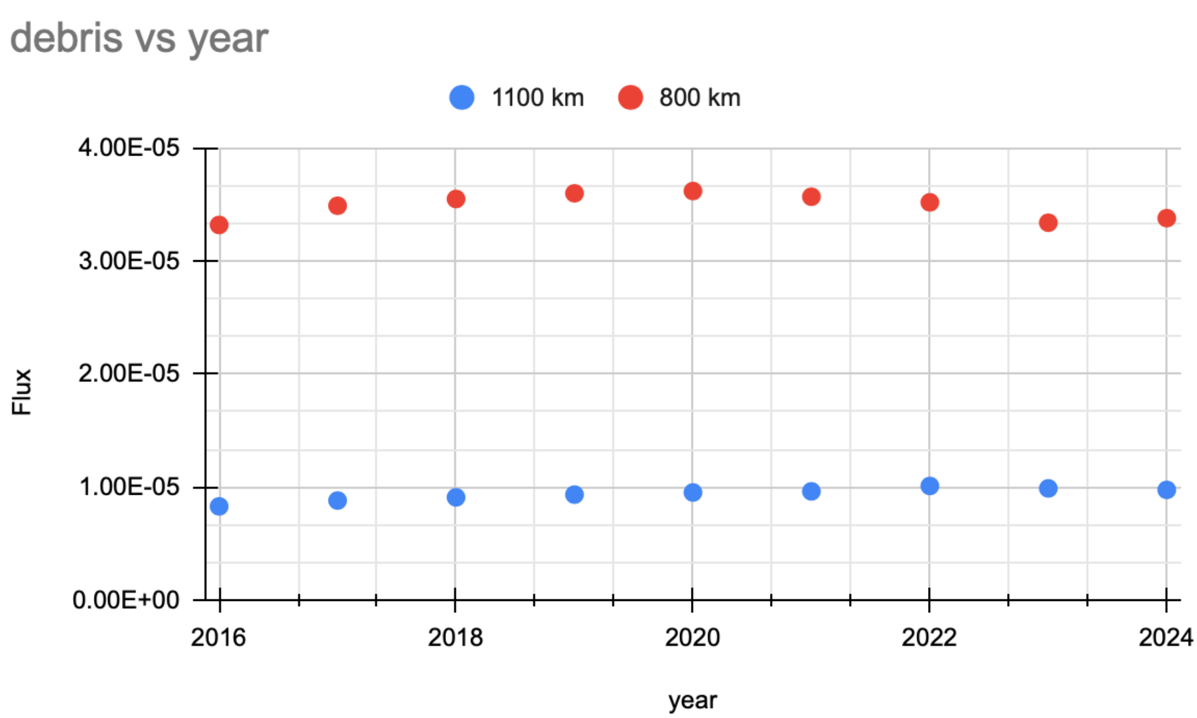


Figure 5. Debris Flux >1 cm at 1100 km and 800km for the years 2016-2024.

When making projections of future debris, using the data exclusively from ORDEM as the basis for projection, a simple regression model suffices. To this end, we started by importing the NASA ORDEM data into Google Sheets. After a significant amount of data clean-up and removal of duplicate entries, we automated this process within Google Sheets. Since large databases can be expected to be imported each year, a new sheet was created to populate time-series data from each of the yearly sheets; and that was done per orbital altitude. As with any data analytics research, data preparation is critical to ensure accurate results and reliable insights. To explore orbital debris prediction in future years, we began by employing the LINEST function in Google Sheets to run a linear regression based on historical data.

The results of this approach are illustrated in Figure 6 for debris >1 cm.

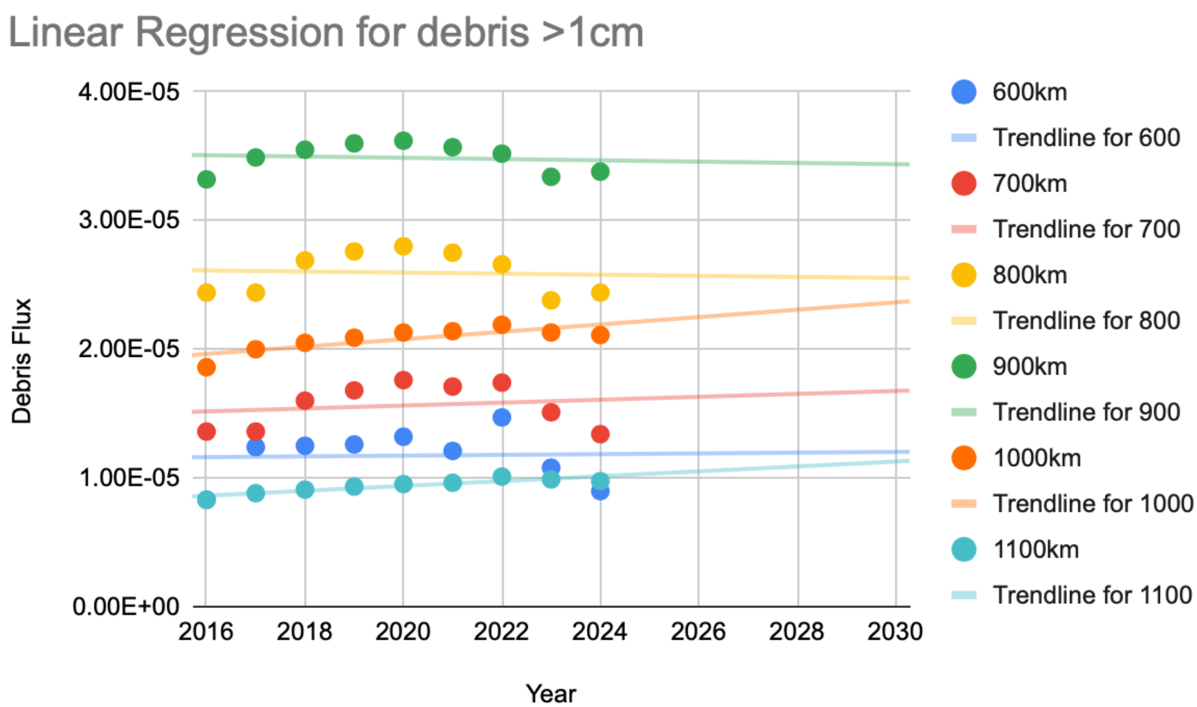


Figure 6. Linear Regression for Debris > 1 cm

However, as noted earlier, a key limitation of this approach is that it does not consider the exponential growth in launch activity. To address this limitation, we gathered FAA data for the US commercial launch sector alone with the goal of projecting this data to the year 2030. To build this model, we first downloaded data from the FAA website on US commercial launches into Google Sheets. We then employed the LOGEST function in Google Sheets to generate an exponential regression. This exponential curve with an R-squared value of 0.95, reveals a strong correlation with our exponential growth assumption. We then generated launch projections with this curve fit going out to 2030. This projection is illustrated in Figure 7.

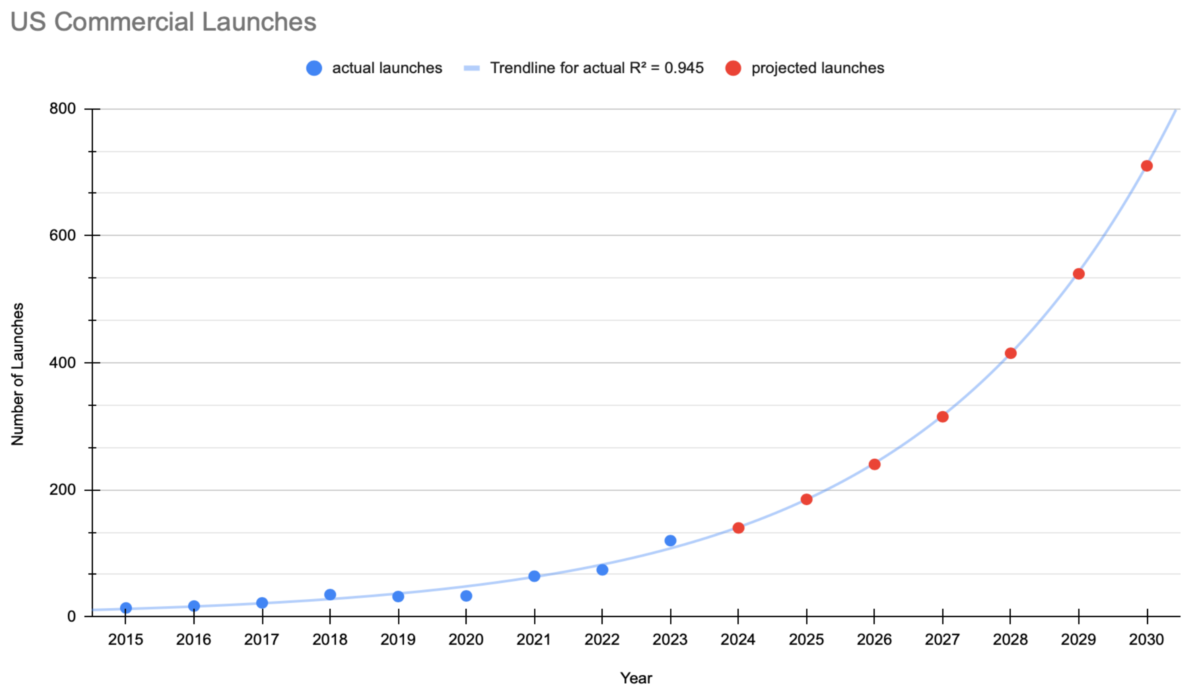


Figure 7. US Commercial Launches (9)

As noted earlier, our research then focused on overcoming the limitation of the previous approach by incorporating a variable to reflect an exponential growth in launch activity. To model the correlation with launch growth to orbital debris, we employed the LINEST function in Google Sheets and ran a linear regression on the exponential growth of launches with the historical debris data. This enhancement helped us realize a more accurate prediction of orbital debris growth. The results are shown in Figure 8. To our knowledge, this is the first paper in the literature to build a model that correlates debris growth with the exponential growth in launches (a relatively recent phenomenon driven primarily by successful SpaceX launches).

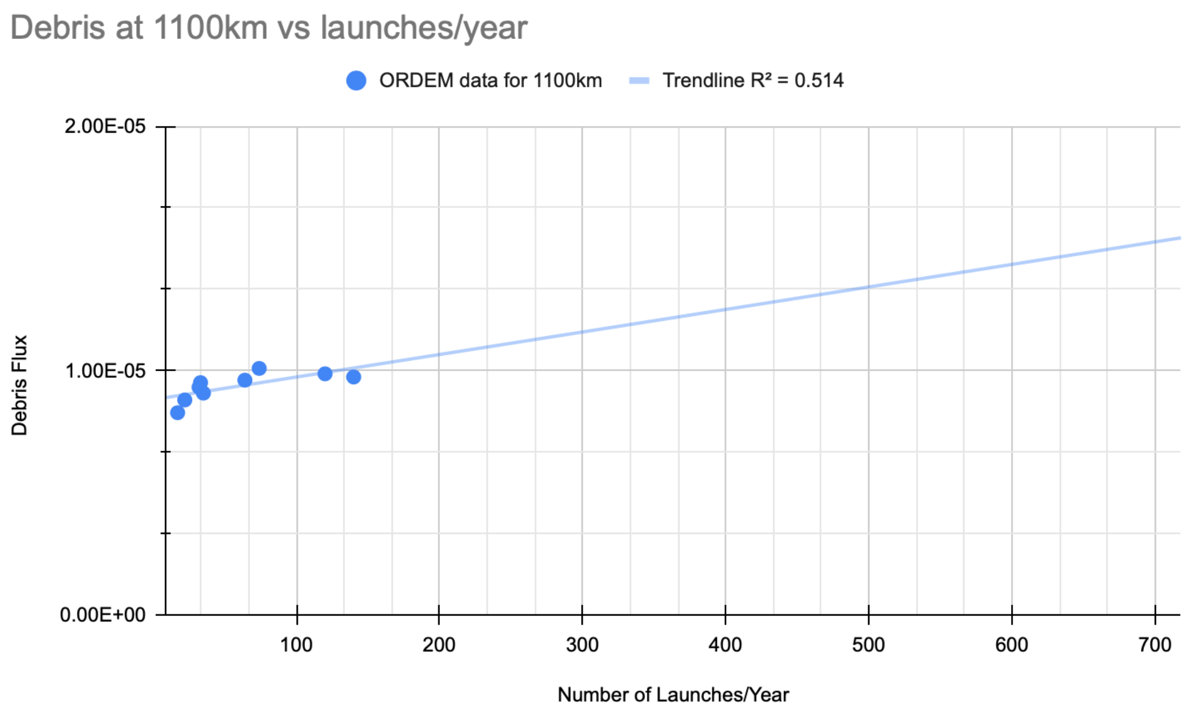


Figure 8. Debris at 1100 km vs Launches Per Year

In this case, we see a significantly greater increase in debris given the exponential growth of space launch through 2030. This growth must be considered to predict and ultimately confront the pressing problem of sustainable space travel and space commerce.

Figure 9 presents a flow-chart that summarizes our overall approach and the data analytics process.

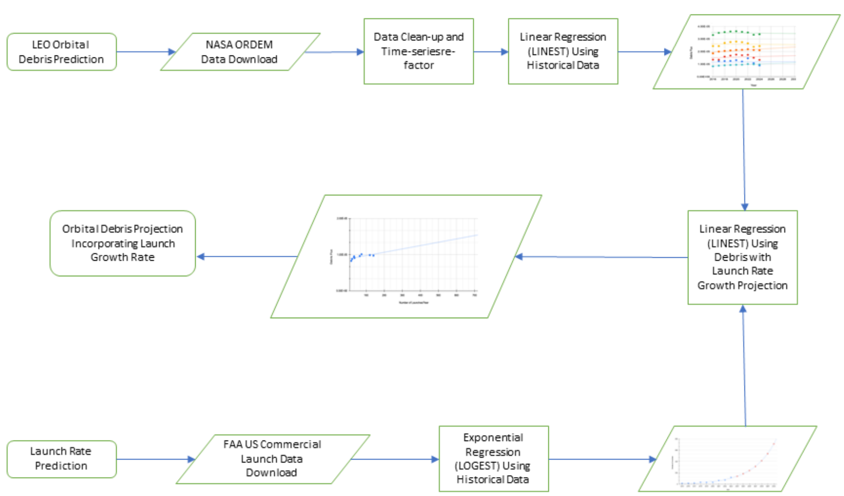
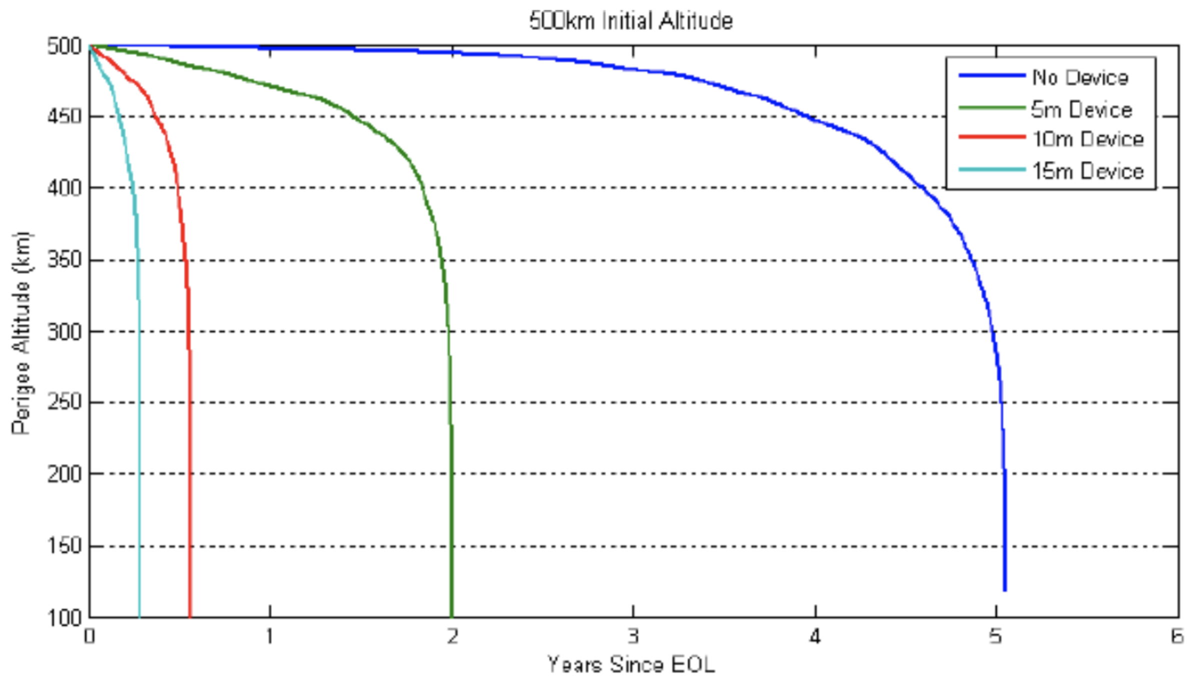


Figure 9. Data Analytics Approach and Process Block Diagram

Future work can include model refinement because the R-squared value of 0.5 indicates a model with relatively low predictive capability.

Thus far, we have discussed the sources of orbital debris. Next, we describe the sinks associated with the natural reduction of debris (6,8). First, solar flares are one-way that orbital debris decay is affected by altering the density of solar flux and thus changing the atmospheric drag in LEO. As solar flares increase, the larger atmospheric drag will cause an acceleration of natural orbit decay and a reduction of orbital debris. Second, there is natural decay even with our baseline solar flux although this can take many years and typically will take 25 years. Figure 10 shows the natural decay rate of a satellite in an initial circular orbit of 500 km (9).

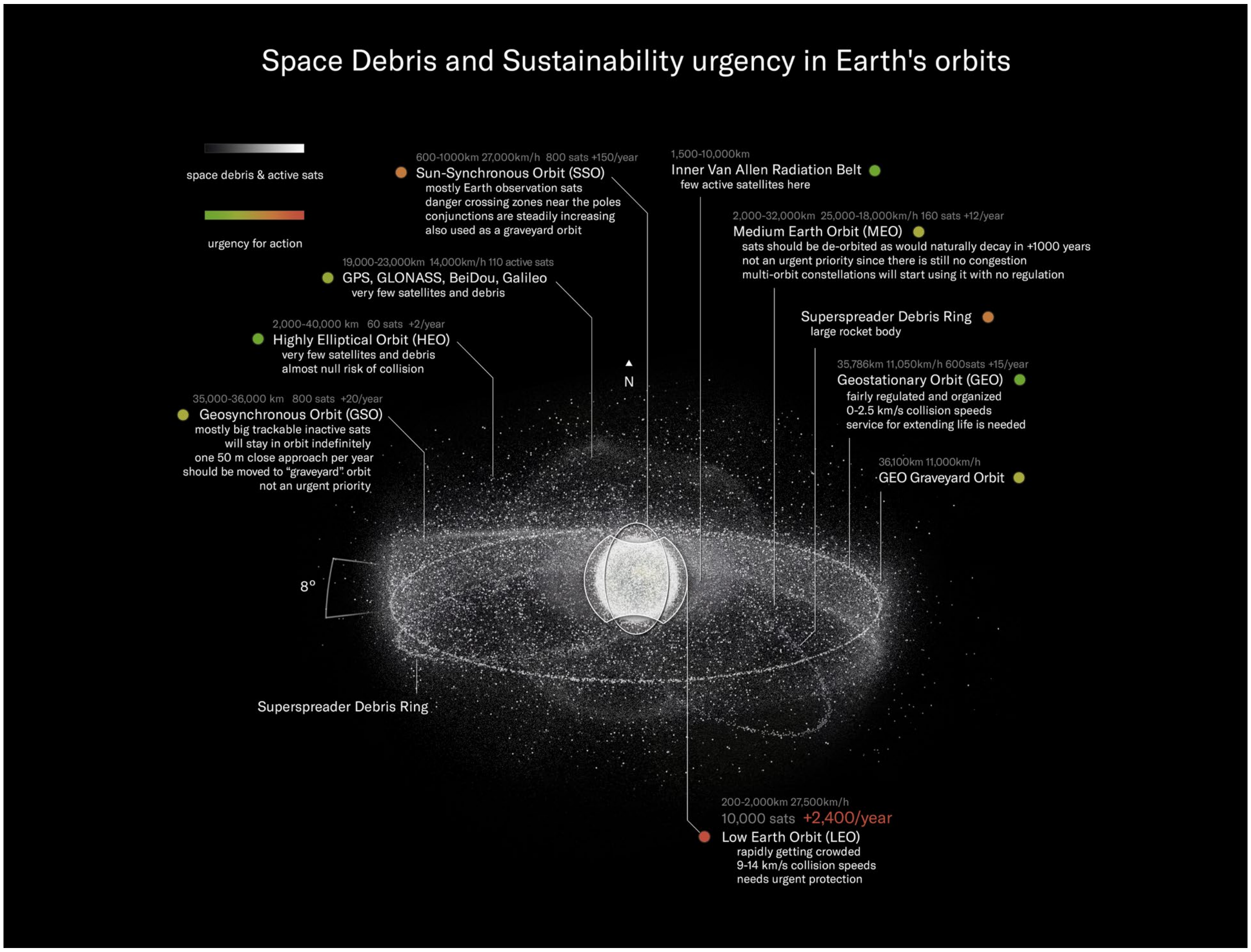


Orbital lifetime (decay) of spacecraft with and without de-orbiting device (for initial circular altitude of 500 km) (Beckett et al. 2004).

Figure 10. Natural decay rate of a satellite in an initial circular orbit of 500km.

Also illustrated is the ability to accelerate this de-orbit with devices that can add to the drag (of various sizes) (9).

It is clear from assembling and analyzing on-orbit debris data as well as prediction models associated with the exponential growth of space launch that this issue of space sustainability must be addressed with urgency. Figure 11 shows the current state of this situation for different orbital altitudes.



Reference 11: pablocarlosbudassi.com

Figure 11. Current State for a Variety of Orbital Attitudes

The Low Earth Orbit (LEO) slot is the most pressing situation today as shown in Fig 11.

In this regard, Donald J. Kessler stated in his seminal paper in 1978 (12) that a runaway debris field could form within an orbital belt making it unusable for space missions. We have shown that with the current exponential growth in launches/year, the Kessler Syndrome phenomenon is a near-term risk.

CONCLUSION

The research findings presented in this paper are intended to inform our understanding of how debris concentrations have changed over the years, and address the challenge of ever-increasing space debris. We used a transdisciplinary data-analytics approach to build a model to predict the growth of orbital debris (7). This model incorporates the exponential growth in space launch activity. We found that a model based exclusively on historical debris data severely under-predicted orbital debris growth. By identifying launch trends and predicting future concentrations, our analysis contributes to the broader understanding of space debris impacts, crucial for developing mitigation strategies and ensuring the sustainability of space activities. The implications of our findings for commercial, defense, and human exploration missions in space are that there is a near-term risk of a Kessler Syndrome phenomenon that would make orbital belts in Low Earth Orbit unusable due to a runaway growth of orbital debris.

Our future work is expected to focus on further tuning of our models that incorporate the exponential growth of space launches on the prediction of orbital debris growth. This follow-on research can include gathering further datasets from ORDEM and correlating these using more advanced data-analytics models that can correlate debris growth to launch rate. These methods would be available in university-level courses in data-analytics. In addition, other factors that contribute to debris growth can be gathered. These include data from ASAT missions and other sources. In closing, we note that while such data is difficult to come by; were we to gain access to such data, our research would produce new and useful insights.

ACKNOWLEDGEMENTS

We wish to thank and acknowledge Dr. Taha Khot, Program Manager, Indian Institute of Technology Bombay, Centre for Machine Intelligence and Data Science for sponsoring Taha's internship in the summer of 2024.

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