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# Satellite Congestion in Earth's Orbits: Exploratory Data and Correlation Analysis of Trends and Future Implications Using Python

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## ABSTRACT

The increasing number of satellites in Earth's orbit has raised concerns about overcrowding and the potential risks of collisions and debris formation. This study analyzes datasets on satellite launches, types (government, commercial, and private), and their orbital altitudes to explore the overcrowding of Earth's orbits. By using Python and libraries such as Pandas and Matplotlib, this research visualizes trends in satellite deployment and identifies potential future challenges for space traffic management. Additionally, the study explores possible future directions for the space industry, focusing on regulation and technology to mitigate overcrowding.

## Introduction

The rapid development of space technology over the past few decades has led to an unprecedented increase in the number of satellites launched into Earth's orbit. Satellites have become integral to a wide range of applications, from global communications and weather forecasting to navigation and scientific research. However, as the space industry continues to expand, the growing number of satellites—both government and private—has sparked concerns about the potential for overcrowding in orbital pathways.

Earth's orbits, particularly Low Earth Orbit (LEO), are becoming increasingly congested, creating new challenges for satellite management and posing risks of collisions, space debris generation, and interference with existing systems. The infamous Kessler Syndrome, a scenario in which the density of objects in orbit becomes high enough that collisions between objects could lead to a cascade of subsequent collisions, has transitioned from a theoretical concept to a real concern as the number of satellites continues to rise.

This paper aims to explore the current state of satellite overcrowding through a data-driven approach. By leveraging open-source datasets on satellite launches, operators, and orbital altitudes, this research will offer insights into the trends shaping Earth's orbits. I used Python and packages such as Pandas and Matplotlib to study and visualize historical and current trends in satellite deployment. It also highlighted areas where orbital congestion is most prominent.

In addition to analyzing the state of Earth's orbits, this paper also examines potential solutions for space traffic management, including regulatory frameworks, technological innovations, and industry collaboration. With the future of space commercialization becoming more prominent, addressing the issues surrounding overcrowding and debris will be vital to ensuring the long-term sustainability of space activities. By exploring these aspects, the research aims to offer a comprehensive understanding of how overcrowding in Earth's orbits can shape the future of the space industry.

# Methods

## Data Collection

I collected data from a variety of online sources, including Kaggle.com and the UCS satellite database. These sources provided comprehensive datasets that included information on satellite launches, operators, purposes, and orbital characteristics, which are essential for analyzing trends in satellite overcrowding.

## Data Cleaning and Preprocessing

The initial datasets contained numerous inconsistencies and missing values that could potentially skew the analysis. To address these issues, I performed several preprocessing steps:

Removing Duplicates: I identified and removed duplicate records to ensure the uniqueness of each satellite entry.

Handling Missing Values: I imputed missing values in the dataset, particularly for orbital parameters where defaults could be reasonably estimated based on the type of satellite and its purpose.

Data Type Conversions: I converted columns to appropriate data types, ensuring that dates, numerical values, and categorical data were correctly recognized by Python for accurate analysis.

## Data Analysis

Using Python, I leveraged libraries such as Pandas for data manipulation and Numpy for numerical calculations. These tools were instrumental in filtering data, performing groupings, and summarizing statistics that highlighted trends in the deployment of satellites over time and their distribution across various orbits.

## Visualization

For visualization, I utilized Matplotlib and Power BI to create a series of graphs that effectively convey the data's story:

Time Series Analysis: I plotted the number of satellites launches over time to identify trends and growth patterns in the satellite industry, especially the sharp increase in launches post-2016.

Orbital Class Distribution: I created pie charts to show the percentage distribution of satellites across different orbits, which highlighted the predominance of Low Earth Orbit (LEO) satellites.

Purpose Analysis: I used bar charts to illustrate the distribution of satellites by their purposes, emphasizing the significant role of communication satellites.

## Denormalization for Visualization

After completing the data analysis, I denormalized the data into a simpler dimension and fact table format. This transformation facilitated more efficient data retrieval for visualizations. The denormalized structure allowed me to create datasets specifically tailored for visual analysis, enabling more dynamic and interactive visualizations that could be easily integrated into the final presentation of the findings.

This comprehensive methodological approach ensured that the study was grounded in robust data handling and analysis practices, allowing for reliable insights into the trends and implications of satellite overcrowding in Earth's orbits.

## Results

### Satellites Launched by Year

The graph shows the Number of Satellite Launches Per Year plotted against the Launch Year on the x-axis. The y-axis represents the Number of Launches, which ranges from 0 to 2000.

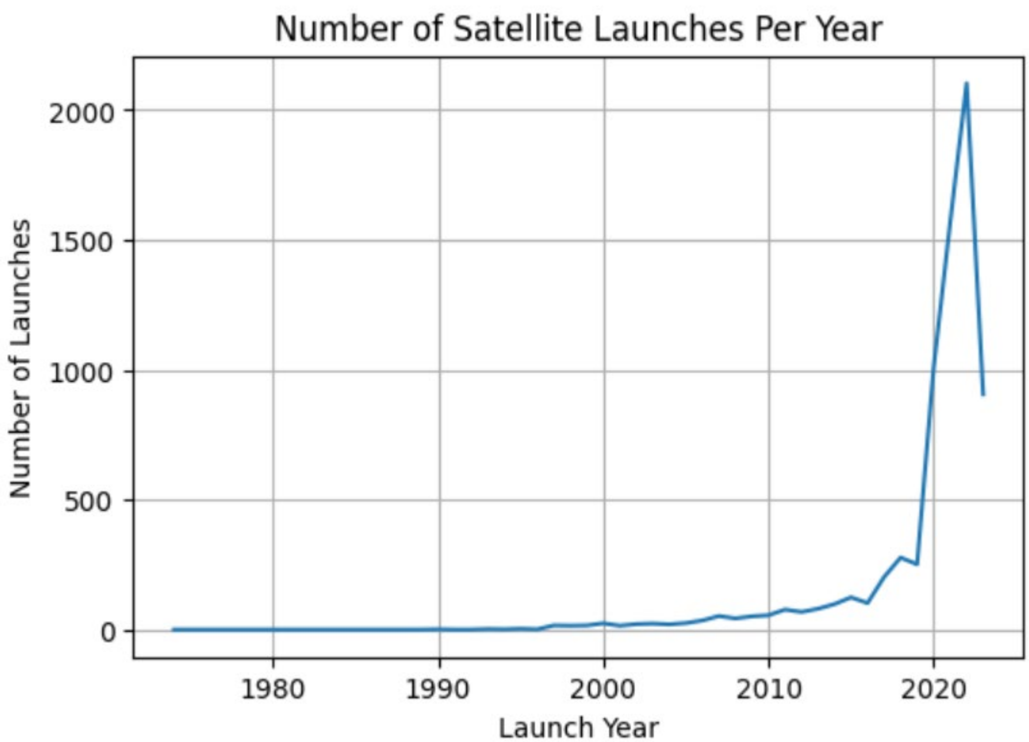



**Figure 1.**

Between the 1970s and early 2000s, the number of satellites launches per year remained relatively stable at very low levels, with launches typically under 500 annually. This period corresponds to the early stages of satellite deployment, dominated by government and military launches, as well as scientific and exploratory missions. During 2000-2015, there is a slight increase in the number of satellite launches, but overall, the rate remains low, likely due to the slow growth in commercial space activities and the high cost associated with launching satellites. After 2016, there is a marked and exponential rise in the number of satellite launches. This sharp increase coincides with the entry of private companies, such as SpaceX, which began deploying large constellations of satellites (e.g., Starlink). The rapid reduction in launch costs through reusable rockets, miniaturization of satellite technology, and increasing demand for satellite-based services (internet, communications, Earth observation) has contributed significantly to this growth. The graph reaches its peak around 2021, with over 2,000 satellite launches in that year. This is a dramatic increase, representing a more than five-fold rise in launches compared to previous decades. However, following this peak, there is a slight dip in 2022, possibly reflecting temporary reductions in launches due to logistical challenges, policy changes, or temporary market saturation.

The sharp increase in satellite launches from 2016 onwards is primarily driven by the commercial sector and reflects a trend towards mega-constellations of satellites, such as those deployed by SpaceX and OneWeb.
The increasing number of satellites being launched annually raises concerns about the overcrowding of orbits, particularly in Low Earth Orbit (LEO), which could lead to a higher probability of collisions and a subsequent increase in space debris.

## Satellites Launched by Earth Orbit

The pie chart depicts the Distribution of Satellites by Orbit Class, showing how satellites are distributed across different orbital regimes. Each orbital class is represented by a portion of the pie chart, with corresponding percentages listed for each category.

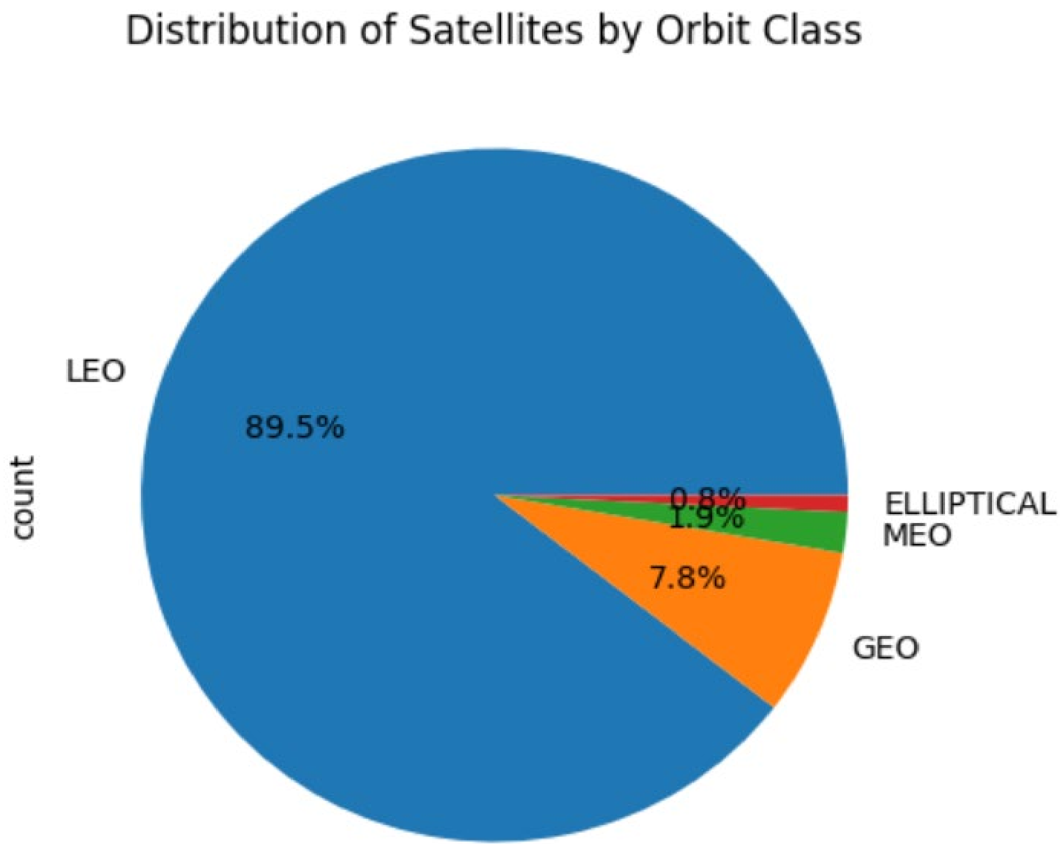



**Figure 2.**

89.5% of all satellites are placed in LEO. This makes LEO by far the most populated orbital region. LEO is popular due to its proximity to Earth, which allows for lower launch costs, reduced latency for communication satellites, and higher resolution for Earth observation. LEO is also heavily favored for mega-constellations such as SpaceX's Starlink.

### *7.8% Of the Satellites Are In GEO, Which Is a Much Smaller Proportion Compared to LEO*

GEO is traditionally used for communications and broadcasting satellites because satellites in this orbit maintain a fixed position relative to the Earth's surface. The high altitude (around 35,786 km) allows for wide coverage, but the distance results in higher latency and costlier launches.

### *1.9% of Satellites are in MEO*

MEO is commonly used for navigation systems, such as the GPS, Galileo, and GLONASS constellations. It offers a balance between the coverage benefits of GEO and the reduced latency of LEO.

### *0.8% of the Satellites Operate in Elliptical Orbits*

These orbits are typically used for specialized missions, including communication satellites serving high latitudes or science missions that require specific orbital patterns.

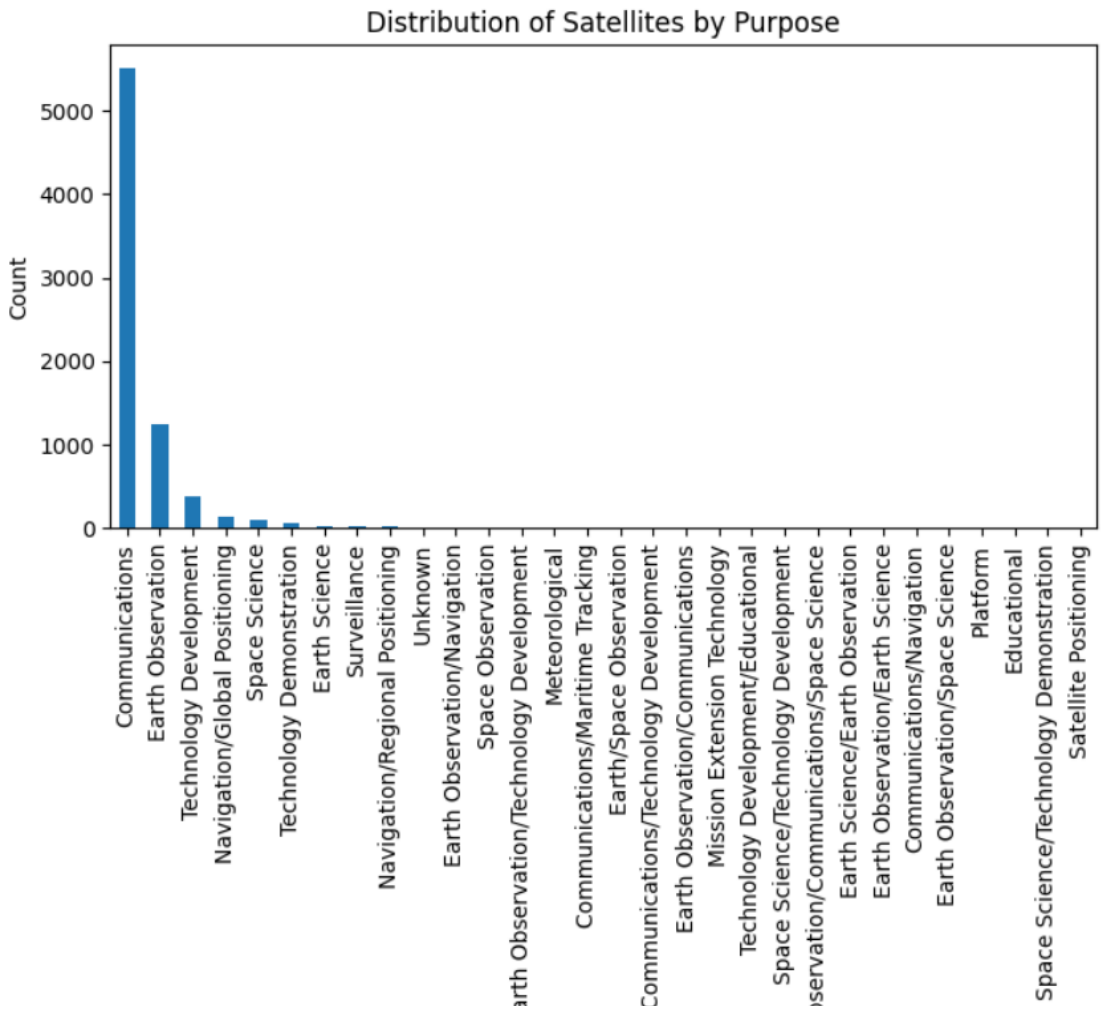
The overwhelming majority of satellites are in LEO, which raises concerns about orbital overcrowding in this region. This high concentration increases the risk of collisions and the formation of space debris, especially given the ongoing deployment of mega-constellations.

While GEO and MEO remain important for certain applications (e.g., broadcasting and navigation), their relatively lower satellite population suggests that the most immediate concern for space traffic management and debris mitigation lies in LEO.

The small number of satellites in elliptical orbits indicates these are niche or mission-specific orbits with fewer congestion issues.

## Satellites Launched by Purpose

The bar chart displays the Distribution of Satellites by Purpose, where each category on the x-axis represents a distinct satellite function, and the y-axis represents the Count of satellites serving that particular purpose.




Communications is by far the most prevalent purpose for satellites, with over 5,000 satellites in this category.

These satellites are crucial for providing global telecommunications services, internet, and data transmission. The surge in satellite communications is driven by projects like Starlink, OneWeb, and other global internet providers deploying large constellations in Low Earth Orbit (LEO).

Earth observation is the second most common satellite purpose, with close to 1,000 satellites.

These satellites are used for monitoring environmental conditions, weather, disaster management, agricultural activities, and remote sensing. They provide valuable data for climate research, natural resource management, and defense applications.

There is a significant number of satellites dedicated to technology development, with a count above 500. These satellites are typically experimental platforms used to test new technologies in space, which include advancements in propulsion, sensors, and spacecraft systems.

Navigation and global positioning satellites, such as those used for GPS, GLONASS, and Galileo systems, have a moderate presence with a few hundred satellites in orbit.
These satellites provide essential services for global positioning and navigation for both civilian and military purposes.

Several other categories, such as Earth science, space science, surveillance, and meteorological satellites, have relatively smaller numbers, often in the low hundreds or fewer.
These satellites are primarily used for specialized purposes like scientific research, military surveillance, environmental monitoring, and analysis.

Satellites by Launch Mass

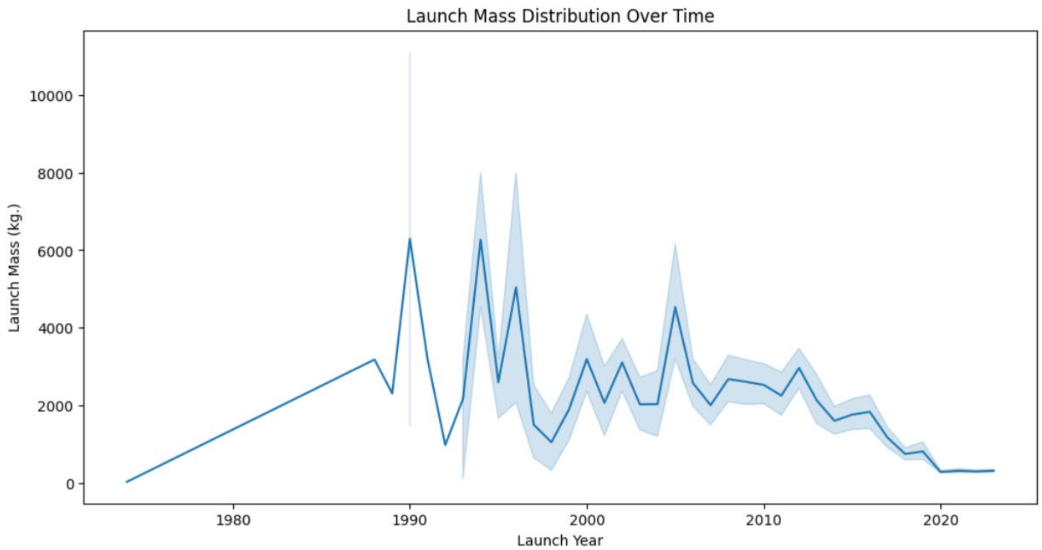



**Figure 4.**

The line graph titled Launch Mass Distribution Over Time displays the mass of satellite launches (in kilograms) over the years from 1970 to around 2020. The x-axis represents the Launch Year, while the y-axis represents the Launch Mass (kg), with the blue line showing the trend and the shaded region around it indicating the variability or uncertainty in the launch mass data.

From the early 1970s to the late 1980s, the average launch mass steadily increased, reaching a peak of around 10,000 kg in the late 1980s.

This period likely reflects the launches of large satellites, such as communication satellites in Geostationary Earth Orbit (GEO) or scientific satellites that required substantial mass for their instruments and onboard systems.

After the peak in the late 1980s, there was a noticeable decline in average satellite launch mass, with more variability in the 1990s and early 2000s. This period could coincide with the development of more efficient satellite technologies, reducing the need for larger, heavier satellites.

By the 2000s, the mass of launches stabilized at lower values, often below 2000 kg. This decline suggests a shift toward more compact, lightweight satellite designs.

In recent years (late 2010s onward), the trend shows a steady decrease in the mass of satellite launches, possibly due to the increasing popularity of CubeSats, nanosatellites, and the miniaturization of electronics and satellite components.

This shift reflects changes in the satellite industry, with more launches involving constellations of smaller satellites, which are used for purposes such as communication, Earth observation, and data collection.

The data indicates a transition in satellite design and deployment strategies. The era of launching large, singular satellites appears to have given way to launching many smaller, lightweight satellites, which aligns with modern trends in satellite constellations (e.g., Starlink).

The reduction in mass over time could also point to advances in satellite technology, where more capabilities are packed into smaller platforms, leading to cost savings in launch operations.

In summary, this graph illustrates the evolution of satellite mass over time, highlighting the shift from larger, heavier satellites to more frequent launches of smaller, efficient ones in recent decades.

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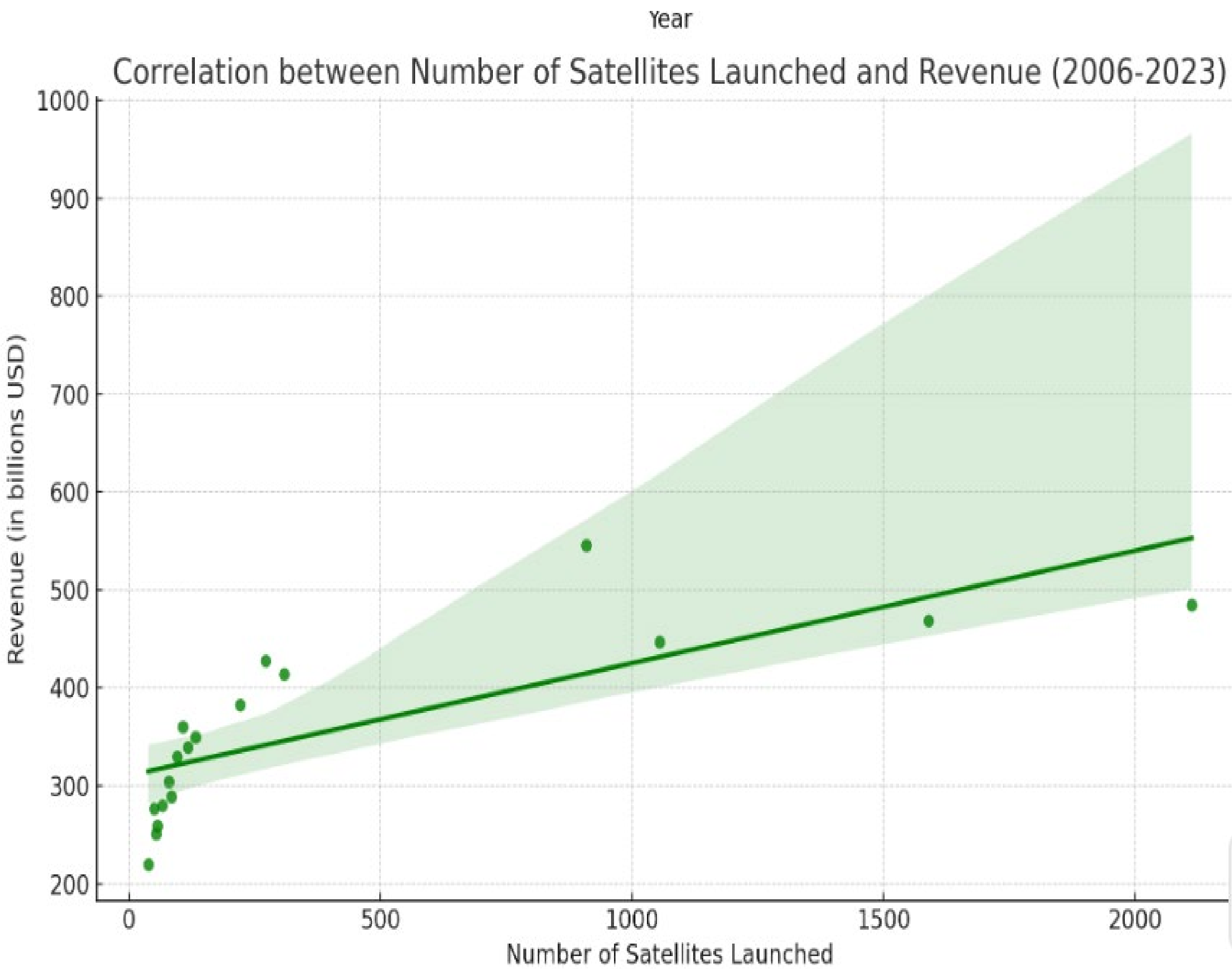
Correlation Between Number of Satellites and Revenue

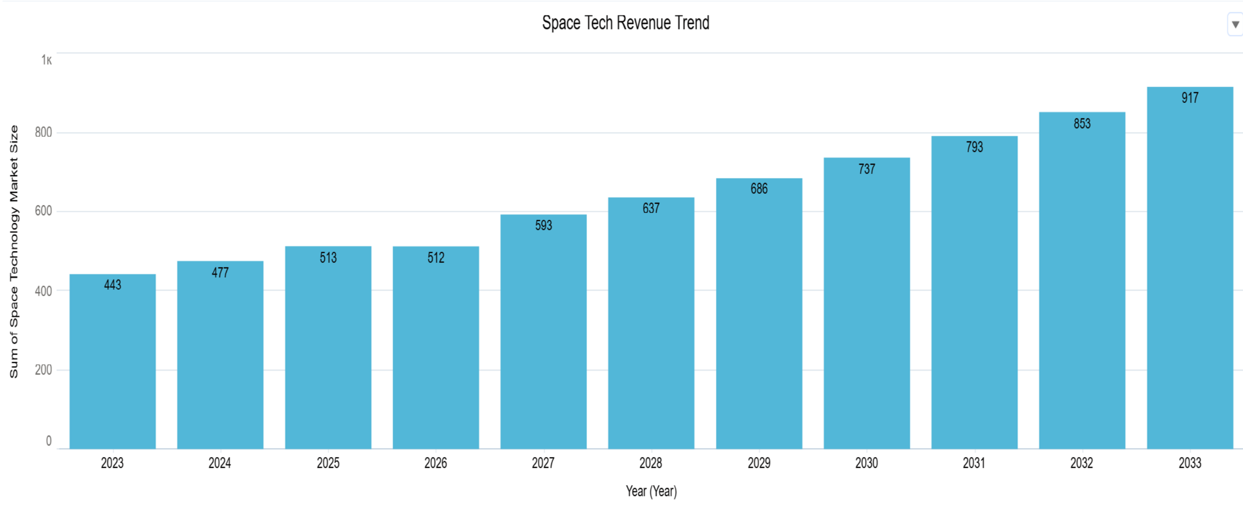



As we can see in the above chart, there is a strong correlation between the number of satellites launched and revenue growth in the space industry. This correlation predicts that private sector will launch more and more satellites to make more profit

## Future Market Size of Space Industry & Space Technology

The space industry is set to grow at a rate of 9%, which is higher than worldwide GDP growth. The total space economy is forecasted to grow to USD 1.7 Trillion by 2034 & anticipated to grow to USD 6.1 Trillion by 2064

The global space technology market size was valued at USD 443.20 billion in 2023 and is anticipated to reach around USD 916.85 billion by 2033, growing at a CAGR of 7.54% from 2024 to 2033. Advancements in satellite technology, launch vehicles, and space exploration missions by commercial players, alongside government agencies, are actively contributing to the expansion of this market hence, aiding in the rapid growth of the space technology market.




A new report from "Novaspace" is forecasting a significant increase in satellite demand through 2033, predicting an average of 3,700 satellites launched annually over the next ten years. This equates to 10 satellites going into space daily, with a total mass of 7 tons per day.

## Discussion

Based on analysis done in the above sections, it's very clear that profit will drive overcrowding on earth's orbit. There is a strong correlation between revenue of the space industry and the number of satellites in earth's orbit. In the next ten years, the space industry will grow at a very fast rate and that will definitely lead to overcrowding of earth's orbit.

Based on the insights gathered from the analysis, the following methods can be considered to mitigate overcrowding in space due to the increasing number of satellites:

### Improved Space Traffic Management (STM) Systems

Enhanced Tracking and Collision Avoidance: Implementing more accurate and comprehensive tracking systems to monitor satellite trajectories in real-time can help prevent potential collisions. Modern sensors, radar systems, and advanced AI algorithms can be used to predict potential collisions and issue avoidance maneuvers.

International Data Sharing: Collaboration between countries, space agencies, and private companies to share satellite position data and collision warnings can improve traffic management and reduce risks.

### Satellite Design for Deorbiting and End-of-Life Disposal

Deorbit Mechanisms: Satellites should be equipped with deorbiting systems (e.g., propulsion systems or tethers) to ensure they are removed from orbit at the end of their operational lives. This would reduce the buildup of non-functional satellites contributing to space debris.

Design for Controlled Re-entry: Building satellites that can undergo controlled re-entry and burn up in Earth's atmosphere could prevent them from becoming long-term debris in orbit. This would particularly apply to LEO satellites that are more prone to overcrowding.

### Active Debris Removal (ADR) Technologies

Debris Capture and Removal: Development and deployment of technologies to actively remove defunct satellites and space debris can help declutter Earth's orbits. These technologies could include robotic arms, nets, or harpoons designed to capture debris and either deorbit it or move it to less populated orbits.

Space Sweeper Missions: Regularly deploying space sweeper missions to clean up orbital debris and defunct satellites could reduce congestion in critical orbits, especially in LEO.

### Promoting Satellite Miniaturization and Multipurpose Satellites

Smaller Satellites and CubeSats: Encouraging the development of smaller, more efficient satellites reduces the mass and size of individual satellites, making it possible to deploy more satellites in a single launch. However, this must be balanced with responsible launch rates to avoid overpopulation.

Multipurpose Satellites: Encouraging the use of multipurpose satellites that can perform a variety of tasks (e.g., communications, Earth observation, and technology demonstration) within a single unit can reduce the number of satellites needed in orbit, thus reducing congestion.

### Use of Geostationary and Higher Orbits

Expand the Use of Geostationary and Medium Earth Orbit (MEO): While LEO is heavily crowded, expanding the use of GEO and MEO for satellites that do not require low-latency communication could alleviate some of the congestion in LEO.

Orbital Altitude Diversification: Encouraging the use of different altitudes within LEO (e.g., lower LEO for communication, higher LEO for observation) can distribute the satellites more evenly, reducing the risk of collision.

## Policy Implications

Currently, the space industry/ sector operates under a relatively sparse regulatory environment, which may not sufficiently mitigate the risks associated with the rapid increase in satellite deployments. Effective policy measures are essential to enforce responsible behaviors among satellite operators, including adherence to best practices for the end-of-life disposal of satellites and compliance with collision avoidance protocols. International cooperation is vital, as space is a global common. Developing comprehensive guidelines that mandate the sharing of orbital and debris data among countries and private entities can enhance situational awareness and reduce the risk of collisions. Furthermore, policies could incentivize the development and adoption of technologies that make satellites safer and more sustainable, such as propulsion systems for active deorbiting. By expanding on these policy implications, stakeholders can foster a space environment that is not only vibrant and commercially viable but also sustainable for future generations.

## Conclusion

The exploratory data analysis presented in this study highlights significant trends and challenges in the rapidly growing space industry. Over the past few decades, the number of satellite launches has increased dramatically, especially in the last 10 years, driven by advancements in satellite miniaturization, the rise of commercial satellite constellations, and the growing demand for global communication and Earth observation services. The data shows a marked shift from launching fewer, larger satellites to deploying smaller, more numerous satellites, primarily in Low Earth Orbit (LEO).

The distribution of satellites by orbit class shows that LEO dominates with nearly 90% of all satellites, indicating a potential risk of overcrowding in this orbital region. With a high concentration of satellites in LEO, concerns about collisions and space debris are becoming increasingly relevant. Similarly, the distribution of satellites by purpose emphasizes the dominance of communications and Earth observation satellites, underlining the critical role these services play in modern life but also contributing to the congestion of key orbital zones.

The analysis of satellite mass over time further reinforces the trend toward smaller, more efficient satellites. This shift points to improvements in technology that allow for lighter, more capable payloads, as well as the increasing use of constellations made up of many small satellites. However, this surge in the number of launches and satellites also raises important questions about long-term sustainability in space.

To address these challenges, the space industry must adopt new regulations and traffic management technologies. As the data shows, without adequate measures, the risk of collisions and space debris in congested orbits could significantly increase, potentially hindering future space exploration and satellite-based services. Sustainable practices, such as debris removal technologies, improved tracking systems, and international regulatory frameworks, will be critical to ensuring the safe and continued growth of the space industry.

In conclusion, while the future of the space industry holds tremendous potential, particularly in providing critical services through satellites, careful attention to orbital overcrowding and sustainable practices will be essential to mitigate the risks posed by this unprecedented growth. Through informed decision-making and innovative technology, the space community can continue to thrive while preserving the long-term usability of Earth's orbits.

## Acknowledgments

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