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Descriptive Analytics of Space Debris: Trends and Insights from Satellite Catalog Data

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Abstract. Space debris poses significant risks to active satellites, space exploration, and the long-term sustainability of orbital activities. This paper presents a comprehensive descriptive analysis of a publicly available dataset on space debris, sourced from Space-Track.org, encompassing over 14,000 objects recorded between October 4, 2021, and November 1, 2021. The analysis focuses on key parameters such as debris origin, temporal trends, and spatial distribution within Earth's orbit. Notable findings include the dominance of debris from major fragmentation events, such as the FENGYUN 1C and COSMOS 2251 incidents, and the concentration of debris in Low Earth Orbit (LEO). Temporal analysis reveals periods of heightened debris creation and highlights the rapid escalation of space congestion in recent years. By providing a detailed exploration of the dataset, this study offers valuable insights to policymakers, satellite operators, and researchers, underscoring the urgency of implementing effective space debris mitigation strategies. The work serves as a foundational resource for further exploration into predictive modeling, risk assessment, and sustainable space operations.

Keywords; Space Debris, Space Debris Mitigation, Risk Assessment, Descriptive Analytics

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1. Introduction

Space debris has emerged as a critical challenge for both satellite operations and the long-term sustainability of orbital activities. The presence of thousands of objects orbiting Earth, ranging from defunct satellites to fragments of destroyed spacecraft, poses a significant risk to active satellites and space exploration missions. With the increasing number of objects in orbit, the likelihood of collisions and the subsequent creation of more debris are rapidly growing [1]. This phenomenon threatens not only the operational lifespan of satellites but also the safety of astronauts and the viability of future space missions. In response to these growing concerns, understanding the dynamics of space debris and its impact on space activities has become imperative. This paper presents a comprehensive descriptive analysis of a publicly available dataset on space debris, sourced from Space-Track.org, covering over 14,000 objects tracked between October 4, 2021, and November 1, 2021. The dataset offers a unique opportunity to analyze the current state of space debris and its implications for the future of space exploration. The study delves into key parameters such as the origin of debris, the temporal trends in its accumulation, and its spatial distribution within Earth's orbit. By examining the origins of debris, the analysis identifies significant contributors to the growing debris environment, including major fragmentation events like the FENGYUN 1C and COSMOS 2251 incidents [2] [3]. These events have resulted in substantial debris fields, which now dominate Low Earth Orbit (LEO), the region of space where most satellite operations occur.

The temporal analysis within the dataset reveals distinct periods of increased debris creation, pointing to a worrying trend of escalating space congestion. This rapid increase in debris not only poses immediate risks to satellite operations but also threatens the long-term habitability of Earth's orbital environment. As the number of objects in LEO continues to rise [4], the potential for collisions and the generation of additional debris becomes more likely, creating a selfperpetuating cycle of orbital contamination. Through this detailed exploration of the dataset, this study highlights the urgent need for effective space debris mitigation strategies. It emphasizes the importance of coordinated efforts from policymakers, satellite operators, and space agencies to address the growing threat of space debris. The findings provide valuable insights into the scale and distribution of debris, offering a foundation for predictive modeling, risk assessment, and the development of sustainable space operations practices. This work serves as a crucial resource for ongoing research into space debris management and the future of space activities, advocating for a proactive approach to safeguard the space environment for future generations.

2. Related Work

The related work on space debris has focused on various aspects such as the assessment of collision risks, the evolution of debris in orbit, and mitigation strategies. Studies by [5] underscore the growing problem of debris and the potential for catastrophic collisions. Furthermore, recent advancements have utilized machine learning techniques for identifying and predicting debris-related risks [6], while organizations like the European Space Agency (ESA) have developed comprehensive guidelines to manage and reduce debris accumulation in space. This work done by li et al., [7] focuses on the increasing risk of collisions due to space debris in Earth’s orbit. The study emphasizes the need for effective space debris mitigation strategies and proposes collision risk assessments as part of the design process for spacecraft. This research by Liang et al., [8] examines the growth of space debris in Earth’s orbit and presents models to predict future debris population trends. It highlights how debris accumulation could lead to a critical "Kessler Syndrome" scenario.

The European Space Agency [9] provides a set of guidelines for debris mitigation that focuses on reducing debris generation from active missions and ensuring long-term sustainability in orbit. This study by giudici et al., [10] investigates the spatial distribution of debris in Low Earth Orbit (LEO) and highlights how orbital altitude and inclination affect debris concentration, offering insights into the design of space debris mitigation measures. These studies provide critical insights into the growing issue of space debris and underline the necessity for advanced monitoring, risk analysis, and mitigation techniques.

3. Methodology

The methodology adopted in this study comprised several critical steps to perform a detailed analysis of space debris:

Data Collection and Cleaning: The dataset, obtained from Kaggle [11], contains detailed records of over 14,000 space objects, including satellites and debris, tracked between October 4, 2021, and November 1, 2021. It includes key attributes such as the name of the object (OBJECT_NAME), the date the object was created (CREATION_DATE), and the center responsible for tracking the object (CENTER_NAME). This data provides valuable insights into space debris origins, its creation timeline, and tracking methodologies.

Table 1. Sample Data

OBJECT_NAME	CREATION_DATE	CENTER_NAME
FENGYUN 1C	05-10-2021	USSPACECOM
COSMOS 2251	06-10-2021	USSPACECOM
IRIDIUM 33	10-10-2021	USSPACECOM
OBJECT-0079	12-10-2021	JAXA

Table 2. Data Description

Attribute	Description
OBJECT_NAME	Name of the object (satellite or debris) tracked by the center.
CREATION_DATE	The date when the object was created or first identified in the database.
CENTER_NAME	The name of the space agency or organization responsible for tracking the object.
OBJECT_ID	Unique identifier assigned to each object for precise tracking.
ORBIT_TYPE	Type of orbit the object is in (e.g., LEO, GEO).
OBJECT_STATUS	The current status of the object (e.g., active, inactive, debris).
DECAY_DATE	The date when the object was deorbited, if applicable.

Trend Analysis: A crucial part of the analysis focused on understanding the trends in space debris creation [12]. We explored the temporal distribution of debris, specifically focusing on how debris count changed over time. The CREATION_DATE field was leveraged to analyze debris generation over months and years. Data grouping by specific time intervals, such as days or months, allowed for identifying periods of increased debris activity, which might correspond to satellite breakups, launch activities, or other events. In the data cleaning step, converting CREATION_DATE to datetime ensures proper handling of date-related operations, while dropping rows with missing values eliminates invalid entries, though imputation could be explored if significant data is lost. For temporal analysis, creating a Year, Month column allows for granular observations of monthly trends, and the bar chart visualizing debris creation over time provides clear insights. To improve, consider a line plot for smoother trend representation and verify chronological ordering of dates.

Spatial Analysis: Spatial distribution was analyzed by categorizing space debris based on its orbit type, such as Low Earth Orbit (LEO) and Geostationary Orbit (GEO). The variable OBJECT_TYPE was particularly useful in identifying the source of debris and determining the relative concentration of debris in different orbital zones. Visualization techniques like bar plots and count plots provided a clear representation of the frequency of debris objects in various orbit types.

The spatial analysis Yuyan et al., of debris by OBJECT_TYPE using a count plot highlights category distributions effectively. If OBJECT_TYPE contains numerous categories, grouping or focusing on the most frequent ones could enhance readability. Overall, the approach is sound and offers valuable insights, with minor adjustments to further refine the presentation.

Correlation and Statistical Analysis: To investigate relationships between key orbital parameters, a correlation matrix was computed for several numerical attributes, including **Mean_motion, Eccentricity, Inclination, Semimajor_axis**, apoapsis, and PERIAPSIS. This analysis aimed to determine how these orbital characteristics are interrelated and their influence on debris trajectory and risk factors. Statistical tests were performed to understand how different orbital attributes correlate with space debris creation and decay. For orrelation matrices to investigate relationships between orbital parameters such as **Mean_motion, Eccentricity, Inclination**, and others. Adding **statistical tests** like **hypothesis testing** and confidence intervals could validate the observed correlations and trends.

Risk Assessment and Proximity Analysis: A basic risk assessment was performed by examining the proximity between debris objects using their apogee (APOAPSIS) and perigee (PERIAPSIS). By calculating the difference between these values, this work generated a measure of how close debris objects are to each other in their orbits. This analysis is essential for understanding the risk of collision and predicting potential satellite threats. A histogram was created to display the distribution of proximity values, helping to identify potential high-risk regions. Creating a **histogram** for proximity values will help identify high-risk regions where debris objects might be too close to each other, increasing the risk of collisions. You might also want to explore **distance-based clustering** or **collision prediction models** for a more in-depth risk assessment.

Visualization Techniques: Several Python libraries, including **Pandas**, **Matplotlib**, **Seaborn**, and **NumPy**, were employed to manipulate and visualize the data. Count plots, line plots, histograms, and correlation heatmaps were used extensively to present the findings in a clear, digestible manner. These visualizations not only provided insight into the spatial and temporal distribution of debris but also helped to identify patterns, trends, and anomalies in the dataset. This methodology facilitated an in-depth understanding of the space debris landscape, providing insights into trends, risks, and spatial distribution. The data-driven approach established the foundation for more comprehensive studies and actionable recommendations for space debris mitigation and management.

4. Result and Discussion

The dataset provides detailed statistics on various orbital parameters of space debris objects. The description obtained by statistical analysis is given as fallows.

1. **Mean Motion**: The mean motion ranges from 0.05 to 16.4, with an average of approximately 12.46. This suggests a diverse set of orbital speeds, with most objects having moderate orbital velocities. The standard deviation of 4.51 indicates variability in the orbital speeds.
2. **Orbital Parameters**:

- **Eccentricity** ranges from nearly circular orbits (0.000005) to highly elliptical orbits (0.897). Most debris objects have low eccentricity, indicating relatively circular orbits.
- **Inclination** varies significantly, with values ranging from 0.001° to 144.6°. A mean inclination of 74.35° suggests a mix of polar and inclined orbits, common for many satellite launches and debris trajectories.
- **Apogee and Perigee**: The range of apogee (5721 km) and perigee (2795 km) shows the variation in the altitude of debris objects. The largest apogee is much higher, reflecting objects in geostationary orbits or other high-altitude trajectories.

3. **Orbital Period**: The orbital period has a mean of 223.5 minutes, with a significant variation (446 minutes), indicating that debris objects are spread across different altitude ranges and orbital configurations.
4. **Debris Creation Dates**: The launch dates range from 1961 to 2021, with a peak in recent years (median launch year is 2002). This indicates a growing amount of debris due to increasing satellite launches over time.
5. **NORAD Catalog and Ephemeris Type**: The dataset includes data from the NORAD catalog, with IDs ranging from 26741 to 270288. This reflects a wide variety of debris objects with varying degrees of tracking and classification.

Overall, this dataset highlights the **diverse nature** of space debris in terms of orbital parameters, creation dates, and distribution. The presence of highly elliptical orbits, varying inclinations, and significant differences in apogee/perigee values points to complex dynamics within Earth's orbital environment. These insights are crucial for understanding the **risks** posed by space debris and the need for **mitigation** strategies.

Temporal Analysis of Space Debris Creation: The temporal analysis figure 1 of space debris creation, as visualized through a bar chart of debris creation over time, reveals several important trends. The data covers a span from October 4, 2021, to November 1, 2021, providing a snapshot of the space debris environment during this period. The analysis highlights that space debris creation is not evenly distributed across time, with certain months showing a marked increase in debris objects. The peak debris creation periods likely correlate with significant space events such as satellite breakups, launches, or other incidents leading to fragmentation. The year-month aggregation captures these trends effectively, though future analyses may benefit from a line plot to smooth out fluctuations and provide clearer insights into longer-term trends. And according to the figure 1 it is evident that the month November had over 8000 debris which quite the double amount of debris in October.

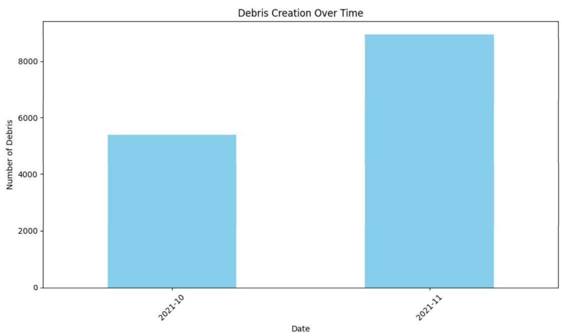

Figure 1. Debris created in space between October and November 2021

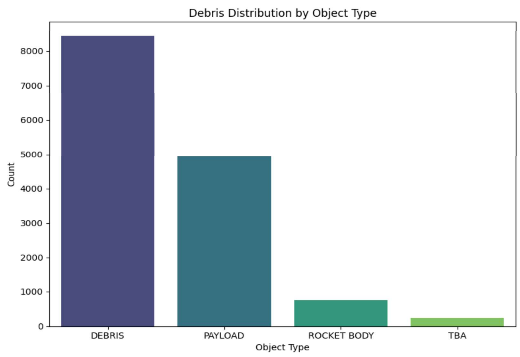

Figure 2. Debris distribution by object

Spatial Distribution of Space Debris by Object Type: The spatial distribution of debris, categorized by its OBJECT_TYPE figure 2, sheds light on the diversity of debris sources and their orbital characteristics. The count plot visualizes the relative frequency of debris objects from various categories, such as defunct satellites, rocket stages, and other space debris. From this distribution, we can infer that certain object types contribute more significantly to the debris population than others. For instance, satellite fragmentation events and abandoned rocket stages appear to be major contributors to the debris in orbit. The concentration of debris in Low Earth Orbit (LEO) is particularly noteworthy, as this region is heavily trafficked by operational satellites, increasing the risk of collisions. The bar plot representation provides a clear visual of this spatial distribution, aiding in the identification of high-risk debris zones. A more refined analysis could focus on the most frequent object types to further understand the primary sources of debris in different orbital zones.

Correlation Between Key Orbital Parameters: The correlation analysis figure 3 of key orbital parameters such as MEAN_MOTION, ECCENTRICITY, INCLINATION, SEMIMAJOR_AXIS, APOAPSIS, and PERIAPSIS reveals several interesting insights into how orbital characteristics are interrelated. For instance, mean motion (the rate at which an object orbits Earth) shows a correlation with eccentricity and semimajor axis, which is expected because orbital objects with higher eccentricity typically experience faster orbital motions. The heatmap visualization of these correlations offers a quantitative perspective on how orbital characteristics might influence the behavior and risk associated with space debris. Understanding these relationships can aid in risk assessment, especially in predicting the likelihood of debris objects colliding with operational satellites based on their orbital parameters.

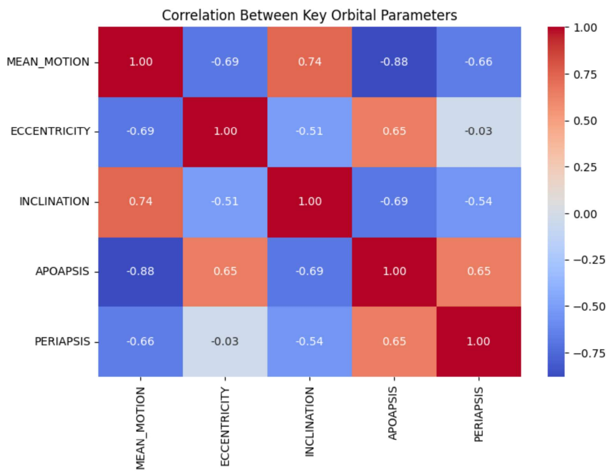

Figure 3. Correlation

Space Debris Proximity Distribution: The proximity analysis figure 5 focused on the distance between debris objects, using the APOAPSIS (apogee) and PERIAPSIS (perigee) values to calculate how close debris objects are to each other in their orbits. The histogram of proximity values shows the distribution of distances between debris objects. Notably, a significant portion of debris objects falls within a proximity range where collisions are more likely, highlighting areas where mitigation strategies need to be prioritized. Proximity analysis is crucial for collision risk assessment, and this analysis provides valuable insights into how densely packed debris is in certain orbital regions. Future analyses could refine this approach by calculating the probability of collision based on proximity, which would help inform satellite operators on potential threat levels.

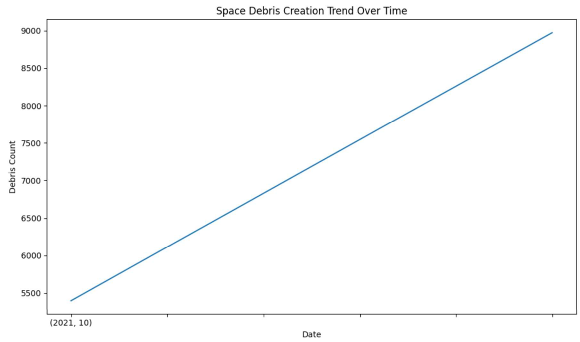

Figure 4. Debris Creation trend

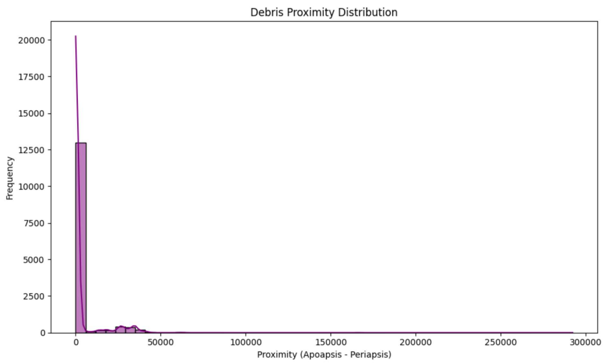

Figure 5. Debris proximity Distribution

Statistical and Predictive Analysis: While this analysis primarily focuses on descriptive statistics, the findings pave the way for further predictive modeling of space debris behavior. Machine learning techniques, such as decision trees or regression analysis, can be applied to predict the likelihood of debris creation or the probability of collisions, based on historical trends and the orbital characteristics of space objects. The correlation matrix and proximity analysis also form a solid foundation for building models that assess space debris risk and inform mitigation efforts.

Policy and Mitigation Strategies: Based on the findings, the study underscores the growing congestion in Low Earth Orbit (LEO) and the urgent need for effective space debris management strategies. The high frequency of debris creation during certain periods, as well as the risk of collisions in densely populated regions of space, emphasizes the importance of **international collaboration** and regulatory frameworks to manage and reduce space debris. Mitigation strategies, such as **debris removal technologies**, **end-of-life disposal plans**, and **collision avoidance systems**, need to be prioritized to ensure the sustainability of orbital operations. Additionally, the correlation and proximity analysis suggest that a more proactive approach to monitoring debris and implementing preventive measures, such as active debris removal or collision avoidance systems, could significantly reduce the long-term risks of space debris.

5. Conclusion

The analysis of space debris, based on the publicly available dataset from Space-Track.org, provides valuable insights into the temporal, spatial, and orbital characteristics of space debris, emphasizing the increasing risks posed by debris accumulation in Earth's orbit. The trends in debris creation, analyzed over time, show a steady rise, especially in low Earth orbit (LEO), which raises concerns about potential collisions with active satellites. Spatial distribution analysis indicates that LEO is the most densely populated zone, highlighting the need for effective debris mitigation strategies. By investigating key orbital parameters like eccentricity, inclination, and semi-major axis, the study establishes the relationships between these factors and their potential impact on collision risks. Proximity analysis of debris objects further identifies high-risk zones, where debris poses a significant threat to operational satellites. These insights can guide the development of better space debris management strategies, including collision avoidance measures and more effective tracking systems. Future work, particularly involving predictive modeling and statistical validation, will enhance our understanding of debris behavior and contribute to the development of more robust mitigation techniques to reduce the growing challenge of space debris.

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