ANALYZING SATELLITE KINEMATICS IN THE EARTH'S ORBITS USING PUBLICLY AVAILABLE DATA

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Abstract

Between 200 and 400 tracked objects annually enter the Earth's atmosphere *(NOAA, 2018)*. The space race began on 4th October 1957, when the first satellite was launched, and now we are delaying launches due to the increasing 'space traffic,' A term used to describe the congestion of objects in Earth's orbit.

According to the Union of Concerned Scientists (UCS) database, a reputable source for satellite data, as of 31st January 2014, there were 1,167 active satellites. This number exponentially increased by almost nine times to 9,900 active satellites as of May 2024, and scientists predict there are more than 170 million objects larger than 1 mm in space. This number is expected to rise, given satellite constellations and miniaturization advances. Though this rise can be considered a technological advancement, it would significantly increase collisions among them, which is a disaster for space debris. According to Donald Kessler (1978), satellite collisions would produce orbiting fragments, each of which would increase the probability of further collisions, leading to the growth of a belt of debris around the Earth. However, with the right measures, this technological advancement can be harnessed for the betterment of space exploration. The need of the hour is not just satellite tracking but reliable satellite tracking. This is not just crucial, but urgent, to prevent these catastrophic events and pave the way for a safer and more sustainable space environment. If not taken into account, it results in destructive collisions, such as the collision of the Yunhai-1 (02) satellite with a piece of space debris, resulting in at least 37 fragments. This event occurred on 18th March 2021, when Yunhai-1 (02) collided with debris from a Russian rocket launched in 1996. Out of these fragments, 23 have since re-entered the atmosphere.

This study, which analyzes satellite speeds and positions as of 2014, is crucial in understanding the exponential increase in space debris resulting from satellite collisions. It provides a relevant and insightful perspective on the issue.

Traditional orbital mechanics relies on deterministic models, where satellite trajectories are computed directly from Newtonian equations of motion. While accurate under ideal conditions, such models cannot account for measurement errors, variations in atmospheric drag, or stochastic events, such as minor debris impacts. This is where Artificial Intelligence and probabilistic methods provide an advantage by incorporating uncertainty and learning from historical data.

Emerging AI methods present significant opportunities for improving satellite tracking and orbital sustainability and are a crucial aspect of this study. An XGBoost (Extreme Gradient Boost) regression model demonstrates near-perfect prediction for satellite velocities.

Techniques such as recurrent neural networks (RNNs) for trajectory forecasting, convolutional neural networks (CNNs) for debris detection, and reinforcement learning (RL) for collision avoidance highlight the role of AI in addressing space debris and collision risks.

Keywords: Kessler Syndrome, Positive Feedback Loop, Space Debris, Orbital Altitude, Orbital Decay, Drag, Perturbations, Orbital Mechanics

1. Introduction

An artificial satellite is an object in space that orbits or circles around a bigger object (Howell, 2022). Its significance is profound in numerous sectors. Satellites travel incredibly fast, clocking in at around 18,000 miles per hour. They enable global communication by transmitting signals for real-time contact over vast distances, connecting remote areas and facilitating global broadcasting. Global Navigation Satellite Systems (GNSS), such as the U.S.
Global Positioning System (GPS), Russia's GLONASS, and the European Union's Galileo, provide accurate positioning, navigation, and timing services. These systems are critical for transportation, military operations, and personal navigation. Satellites with sensors and cameras monitor the Earth's surface, atmosphere, and oceans for weather forecasting, climate monitoring, disaster management, etc. They are used to study space and observe distant stars, galaxies, and other astronomical objects phenomena, like the Hubble telescope. Military satellites are used for surveillance and communication. They enhance national security by providing critical intelligence and supporting defence operations.
Satellites can be at varied distances from the Earth, from the Low Earth Orbit (160 – 2,000km) to the Geostationary Orbit, the furthest away, at 35,786 km (22,236 miles) *(Ground Control)* (Fig 1). Only 10% of satellites orbit the Medium Earth Orbit (MEO), and they are used almost exclusively for GPS and related services rather than communications *(Ground Control)*.

This study aims to use the positions and speeds of 600 satellites in orbit around the Earth to relate it to the exponential increase in space debris resulting from satellite collisions.

The satellites' locations are determined using tracking from ground stations, which uses radar, signal Doppler, and laser reflectors to pinpoint a satellite's position and maintain an understanding of its orbital elements *(Forbes, 2018)*. Various factors influence the speed of satellites, including Orbital Altitude, Gravitational Force, Orbital Type, Mass of the Earth, Velocity, Drag, Perturbations, Orbital Mechanics, etc. A satellite's tracking telemetry and control (TT&C) system is a two-way communication link between the satellite and TT&C on the ground. It allows a ground station to track a satellite's position and control its propulsion, thermal, and other systems *(Labrador, 2024)*. It can also monitor a satellite's temperature, electrical voltages, and other vital parameters *(Labrador, 2024)*.

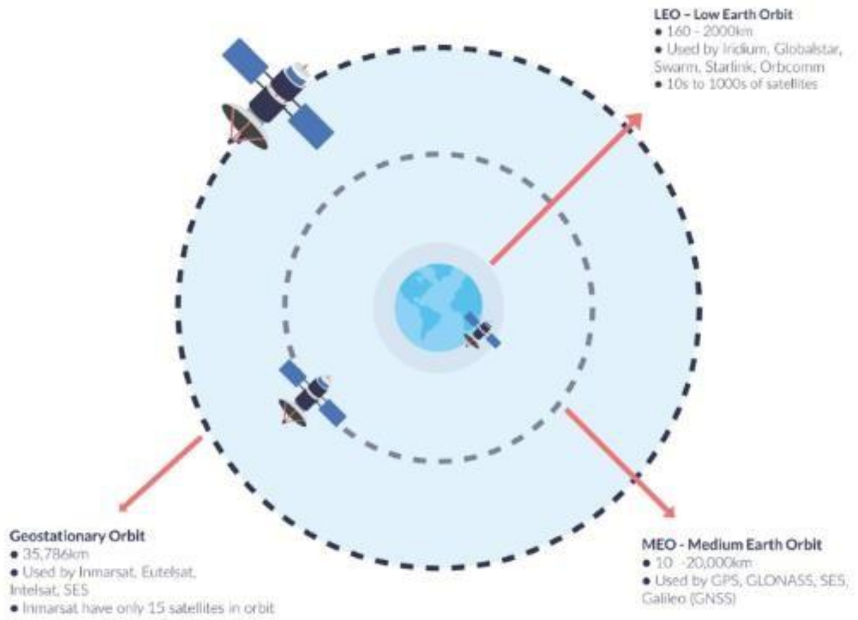

Figure 1- Satellite Orbit Map

As the space age progresses, more satellites will be sent into space, but the problem arises because space is becoming overcrowded. More satellites mean more collisions, which result in more space debris, which is dangerous for the other satellites; it is a positive feedback loop.

2. Literature Review

Till around the mid-20th century, NASA had to worry only about meteoroids in the asteroid belt as space debris. Donald Kessler, a NASA scientist, performed complex calculations to conclude that a similar phenomenon would soon happen in the Earth's orbit.

He published a paper in 1978 proposing this scenario, predicting satellite collisions in the Earth's orbit by 2000. He said that just like in the asteroid belt, these satellite collisions would trigger a domino effect, a chain reaction of collisions, creating a large quantity of fragmented material, which would cause more collisions, creating more debris, and so on. His main point was that it would be nearly impossible to stop once it started. This self-perpetuating phenomenon, this domino effect, became known as the Kessler Syndrome.

In recent years, AI has been increasingly applied in space situational awareness. Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) models have shown promise in forecasting satellite trajectories as time-series data. Bayesian Neural Networks can quantify uncertainty in collision predictions, while Graph Neural Networks (GNNs) model constellations and debris fields as interconnected systems to identify high-risk regions. For debris detection, Convolutional Neural Networks (CNNs) and object-detection models, such as YOLO, have been employed on telescope and radar imagery. These approaches extend traditional orbital mechanics by incorporating learning from historical data, enabling more adaptive and real-time predictions.

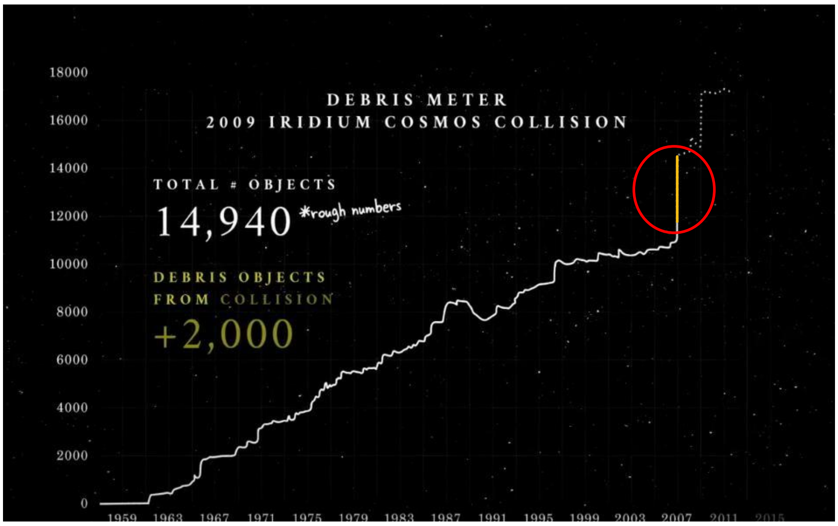

Figure 2- Increase in space debris post the collision

The first catastrophic accidental collision that got everybody's attention occurred on 10th February 2009. It was the first collision between two intact satellites- the inactive Russian communication satellite Kosmos 2251 and the active American communication satellite Iridium 33 at the relative velocity $11 kms^{-1}$. Much debris is generated when something like that occurs (Fig 2). These two events (the Iridium-Kosmos collision, February 2009, and a Chinese anti-satellite missile test, January 2007) more than doubled the number of fragmentation objects being tracked. The deliberate destruction of the Fengyun-1C weather satellite (in a circular orbit near 850 km) in January 2007 caused the single largest fragmentation event in space (to date), with more than 2600 catalogued fragments *(Hobbs, Stansberry, de Carvalho, 2019)*. Furthermore, it has been reviewed that space debris smaller than 1cm can be shielded from, and those larger than 10cm are reliably trackable and avoidable. Concern arises with particles between 1-10cm, which are destructive and cannot be reliably tracked. They are too large for shielding to withstand and too small to detect accurately. The total number of space objects of more than 10 cm sized in LEO is expected to be about 60000 by 2030 *(ISRO)*.

3. Data collection

The dataset used is the answer_key.csv file of "**Predict the positions and speeds of 600 satellites**" by **Ismail Dawoodjee** from Kaggle. The description quoted- "The original datasets were obtained from the International Data Analytics Olympiad 2020 (IDAO 2020) Competition, provided by the Russian Astronomical Science Centre. Being a competition, IDAO does not provide the answer key for their test dataset. However, their train dataset was prepared so that testing one's algorithm could be done easily.

Satellite positions and speeds (henceforth, they will be collectively referred to as the "kinematic states") can be measured using different methods, including simulations. This dataset has two kinds of simulators: the precise simulator and the imprecise simulator. We refer to measurements made using the precise simulator as the "true" kinematic states of the satellite and measurements made using the imprecise simulator as the "simulated" kinematic states.

The aim is to make predictions for the true kinematic states of satellites in the final seven days of January 2014.

The answer_key.csv file includes the answers to the position (coordinates) in x, y and z and the velocities in the three planes as Vx, Vy and Vz, respectively."

3.1. Code used

The algorithm that had been used for predicting the true x, y, and z coordinates and Vx, Vy, and Vz included (taken from **0.9964 train.csv acc | 0.76 test.csv acc** by **Ashwin Gupta**, 2022)-

```
import numpy as np import pandas
as pd import seaborn as sns
import matplotlib.pyplot as plt
from sklearn import preprocessing
train = pd.read_csv('../input/predict-the-positions-
andspeeds-of-600-satellites/jan_train.csv') test =
pd.read_csv('../input/predict-the-positions-andspeeds-of-600-
satellites/jan_test.csv') key =
pd.read_csv('../input/predict-the-positions-and-speedsof-600-
satellites/answer_key.csv')
train.info()

train['epoch'] = pd.to_datetime(train['epoch'])
sns.pairplot(train)
```

4. Methodology

The true x-coordinates of satellites were analyzed through a histogram, which suggests that it follows a normal or Gaussian distribution, and a few observations were made-

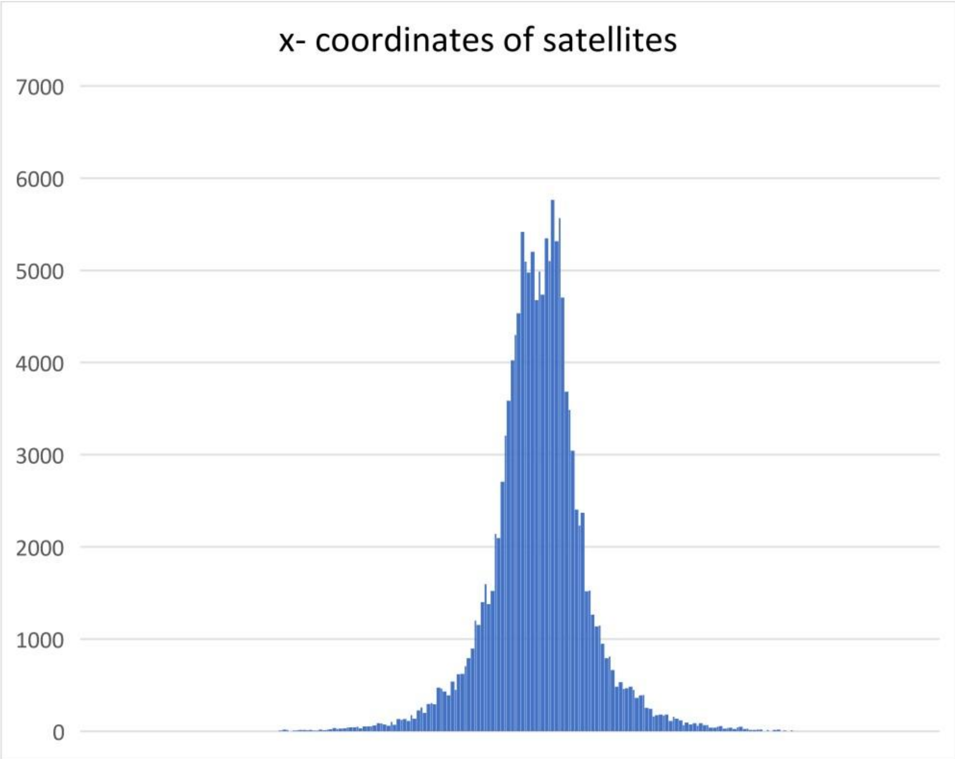

Figure 3: Histogram of the true x coordinates of satellites.

1. Central Tendency: The central peak suggests that many satellites have X coordinates clustered around a central value. This central value likely represents the satellites' average or most common X coordinate.

2. Satellite Distribution: The shape of the histogram suggests that most satellites are concentrated around the central X coordinate, with the number of satellites decreasing as the X coordinates move away from the centre. This could imply that the satellites are positioned in a manner that centres around a particular X coordinate, which might be significant for their orbital mechanics or operational purposes.

3. Outliers: The relatively few data points far from the central peak suggest there are not many satellites with X coordinates that are extreme outliers. This indicates that most satellites have X coordinates that are just a short distance from the average.

The above observations may lead to the following conclusions-

1. Operational Concentration: The concentration of satellites around a central X coordinate may indicate a preferred region or an optimal operational zone in space. This could be related to the specific function of the satellites, such as communication, GPS, or scientific observation.

2. Orbital Patterns: The normal distribution suggests that the satellites likely follow specific orbital patterns that result in their X coordinates being distributed this way. The central

peak could correspond to a specific orbital path or preferred or most commonly used altitude.

3. Design and Deployment Strategy: The deployment strategy of these satellites might aim to maintain a balanced distribution around a certain X coordinate, which can be inferred from the symmetric and bell-shaped distribution. This balance could be essential for maintaining coverage, reducing collision risk, or optimizing performance.

While this study employs statistical methods to analyze satellite positions and velocities, future extensions could utilise AI models for improved prediction accuracy. For example, gradient-boosted decision trees (such as XGBoost) can learn from structured orbital datasets to predict velocity components, while LSTMs are well-suited for forecasting orbital trajectories over time. Kalman filter AI hybrids could also be applied to reduce noise in publicly available orbital data.

5. Challenges in Orbital Operations

5.1. Collisions

All collisions, accidental or otherwise, create a significant accumulation of debris in orbital motion around the Earth. It accounts for 95% of the objects in Low Earth orbit and comes in all shapes and sizes. Technically, it is defined as any nonfunctional object in orbit, like rocket thrusters and defunct satellites, but the vast majority are little bits and pieces called fragmentation debris. These fragments come from explosions caused by residual fuel and other explosive energy sources self-igniting under the extreme conditions of space. As catastrophic and messy as these explosions are, collisions are even worse due to the incredible amount of kinetic energy involved. Even a fleck of paint can cause damage, as was noticed in 2016 when a paint particle compromised the ISS (International Space Station) window.

$$\text{KE} = \frac{1}{2} \times mass \times (velocity)^2$$

$$\text{KE} = \frac{1}{2} \times mass \times 7500\ \frac{m^2}{s^2}$$

$$\text{KE} = \frac{1}{2} \times 0.002\ kg \times 7500\ \frac{m^2}{s^2}$$

$$\text{KE} = 56{,}250\ kg\ \frac{m^2}{s^2}$$

KE= 56250 Joules

Where 'm' is the mass of an object in space, here, the object is considered to be a screw. Hence, its weight is substituted into the equation, and v is the velocity of an object in space.

At the velocities, objects travel in low earth orbit (speeds known as hypervelocity); even an object as tiny as a screw can deliver an incapacitating strike to a satellite. As more satellites are launched into space, the chances of a collision increase.

AI can address the challenge of conjunction analysis by using Bayesian Neural Networks to predict collision probabilities under uncertainty, and GNNs to analyze prominent satellite constellations as complex networks. This enhances risk assessment and facilitates more informed decision-making compared to purely deterministic models.

5.2. Duration of objects in space

Besides collision, the problem worsens when considering how long objects can remain in orbit. Depending on elevation, debris in LEO may remain for years, decades, or even centuries before their orbit naturally decays enough to re-enter the Earth's atmosphere.

ENVISAT was a defunct 8-tonne satellite operated by the European Space Agency until it lost contact in 2012. It became a massive piece of junk in the dense region of Earth's orbit. If not removed, it will remain in orbit for 200 years.

6. Mitigation Strategies

1. Deplete all onboard sources of stored energy and disconnect all every generation sources when they are no longer required for mission operations to control explosions in space.

2. Removal of all spacecraft and upper stages from the environment promptly through manoeuvre to an orbit from which natural decay will occur within 25 years of EOM (End of Mission) and 30 years from launch- either by moving it up to a designated "graveyard orbit" if satellite position>1400km to reduce threat to active satellites or more ideally, lowering its altitude to disposal orbit if satellite position<1400km so it will burn up in the atmosphere sooner (within 25 years)

These two things would make space flight safer in the future- by maintaining the effect of the Kessler Syndrome on an acceptable level and preventing it from increasing. In an interview, Donald Kessler stated, "It is going to take removing 500 intact objects over the next 100 years to stabilize the Low Earth Orbit environment again," which means five objects per year for the next 100 years.

3. Follow all the guidelines, like the Space Debris Mitigation Guidelines brought out by IADC (Inter-Agency Space Debris Coordination Committee), in space activities and comply with them to the maximum extent possible and practicable under the constraints of national priorities, payload availability, and mission operations *(ISRO)*.

   Promising ideas for removal of space debris-

   a. Tethers and space tugs are reusable and can grab multiple objects per launch.
   b. Ground or space-based lasers can deorbit objects by shooting them
   c. The University of Surrey is controlling a spacecraft called RemoveDEBRIS, which will use a harpoon to grab onto debris.

AI also holds potential in active debris management. CNN-based vision systems can classify debris in real-time from telescope imagery, enabling the detection of smaller but hazardous fragments. Reinforcement Learning (RL) can optimize debris-removal missions by selecting fuel-efficient sequences of objects to target, while genetic algorithms can design optimal trajectories for space tugs and harpoons. These methods offer autonomous and scalable solutions for long-term debris reduction.

7. Conclusion

Presently, orbital data in the public domain need more accuracy, leading to ambiguity in the decision-making process pertinent to collision avoidance manoeuvres *(ISRO)*.

The histogram (Fig 3) of satellite true X coordinates shows a symmetric, bell-shaped distribution centred around a mean value, indicating a normal distribution. Most satellites are clustered around a central X coordinate, with variability decreasing symmetrically on either side. This implies an operational concentration and specific orbital patterns with fewer outliers. The central peak suggests a preferred operational zone, likely related to the satellites' specific functions, such as communication or GPS. The normal distribution indicates a balanced and strategic deployment to maintain coverage, optimize performance, and reduce collision risk.

Like other environmental and generational problems, Kessler syndrome is invisible to us. If we continue to do spaceflight without improving, then in a few decades, some regions of space might not be usable anymore for spaceflight or might be much too risky to go there. Mitigation strategies include active debris removal, improved collision avoidance, and end-of-life disposal plans. Future efforts should focus on enhanced tracking, advanced predictive models, active debris removal technologies, and international collaboration to ensure the sustainable use of space.

The entire space has unlimited space, not the Earth's orbit.

Although this study applied statistical techniques to assess satellite kinematics, AI models such as LSTMs, CNNs, and RL-based planners represent the next step in ensuring orbital sustainability. Their integration into satellite tracking, collision avoidance, and debris removal strategies will be crucial in preventing the escalation of the Kessler Syndrome and maintaining the long-term viability of Earth's orbit.

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