

MEASURING SUSCEPTIBILITY TO KESSLER SYNDROME OF ACTIVE SATELLITES THROUGH CONJUNCTION PROBABILITY ANALYSIS

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TERMINOLOGY (BASICS)

- ▶ “Kessler Syndrome” is a term coined by Donald Kessler and Burton Cour-Palais in 1978 to describe a scenario in which the number of satellites orbiting Earth climbs so high that catastrophic collisions between them become nearly unavoidable.
 - ▶ Currently a hypothetical scenario, but it is possible with an increasing number of satellites.
- ▶ Conjunction probability analysis is simply a process to analyze the orbits of two objects, usually artificial satellites, and find the probability that they collide, along with a few other statistics.
- ▶ A Two-Line-Element (TLE) is a package of data, two lines long, that stores orbital parameters for satellites, which are values that describe a satellite’s orbit, essentially how oval-shaped it is, how tilted, etc.

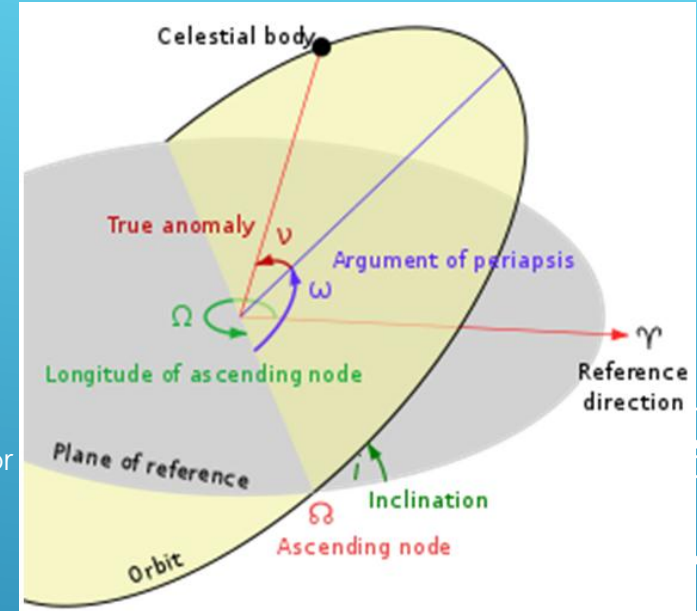
TERMINOLOGY (ORBITAL MECHANICS)

▶ Orbital Parameters

- ▶ Semi-major axis (a)
 - ▶ Describes the radius of the orbit (average of closest and farthest point)
- ▶ Inclination (i)
 - ▶ Describes slant of the orbit
- ▶ Eccentricity (e)
 - ▶ Describes circularity of the orbit
- ▶ Right Ascension of Ascending Node (Ω)
 - ▶ Describes angle between a universal "X-axis"* and the point where the satellite crosses the Equator going north
- ▶ Argument of Periapsis (ω)
 - ▶ Describes the orientation of the orbit in its plane
- ▶ True Anomaly (ν)
 - ▶ Describes the position of the satellite as a degree measure on its track at a certain epoch

▶ Orbit Types

- ▶ Lower Earth Orbit (LEO)
 - ▶ LEO orbits are usually close to the surface, providing details and having periods (time it takes to make one lap around the Earth) of approximately 90 minutes. It's used for most satellites because it's easy to launch to and provides a good angle.
- ▶ Geosynchronous
 - ▶ Geosynchronous orbits are very far from the Earth, as their main goal is to align with the Earth's rotation rate and stay at a fixed point above it or return to that point at the same time each day. This is mostly used for communication satellites.



Credit:

<https://www.astronomicalreturns.com/p/section-43-six-orbital-elements.html>

CONSTELLATIONS

- ▶ As we launch satellites into space, there has been an increasing tendency to want to launch them in large groups. This allows satellites to “work together to perform a service” (About Satellite Constellations – CPS, 2024). Most commonly, this service is used to provide internet, but it can also be for simple communication or GPS.
 - ▶ As opposed to individual satellites being launched, e. g. Sputnik, ISS
- ▶ These are called constellations. Some large constellations include SpaceX’s Starlink and Amazon’s Amazon Leo, which are both intended to provide high-quality global broadband internet access.
- ▶ These satellites, while they provide beneficial services, can create lots of space junk and even pose risks themselves. This is essentially the entire goal of this project. This project aims to measure the impact of major constellations like Starlink.



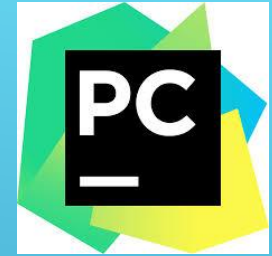
Credit:
https://en.wikipedia.org/wiki/File:Starlink_Logo.svg



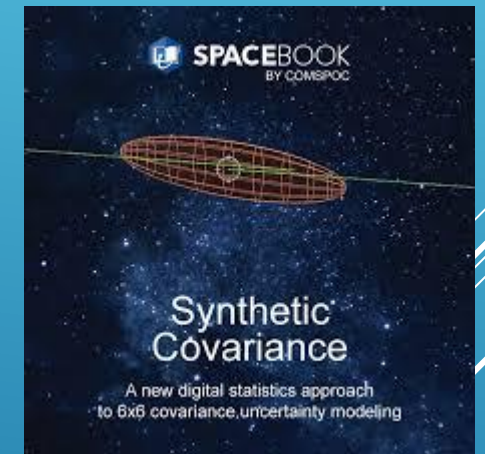
Credit:
<https://www.linkedin.com/showcase/amazon-leo/>

METHODS

- ▶ Since there are nearly 30,000 objects that I would be working with, it is completely ridiculous to do this by hand. Even with a powerful calculator, this would take weeks, so I used PyCharm, an IDE specialized in Python, a versatile coding language that is perfect for this task.
- ▶ Using the *requests* library, I originally gathered data from space-track.org, a website maintained by the US Space Force, at least until I mistakenly broke a regulation they had in place and had my account suspended.
- ▶ I turned to another source, called Spacebook by COMSPOC, which is like space-track, just not considered as official (but not less accurate). From there, I downloaded 29,521 of the most recent satellite TLEs from their website.
- ▶ However, I didn't just need current satellite TLEs. The nature of TLEs makes them flawed, as they cannot exactly pinpoint a satellite's location, merely identify where is it most likely to be. I needed to find information about these satellites' covariance data (essentially describing the satellites as a blob of uncertainty), which would allow me to more accurately depict them and make computing the final probability of collision more accurate.
 - ▶ Frequently, to solve this, a standard covariance is assumed. This is obviously flawed, as it can cause the creation of false positive and negative conjunctions. What makes this different is that I used historical TLE data to calculate the covariance information myself, leading to a more accurate picture.
 - ▶ Importantly, this means I had to take colossal numbers of satellite TLEs to get an accurate figure for each individual satellite, with the final number of historical TLEs I gathered being around 15.2 million.
 - ▶ I also gathered these from Spacebook with the *requests* library, taking extensive precautions so as not to affect server performance.



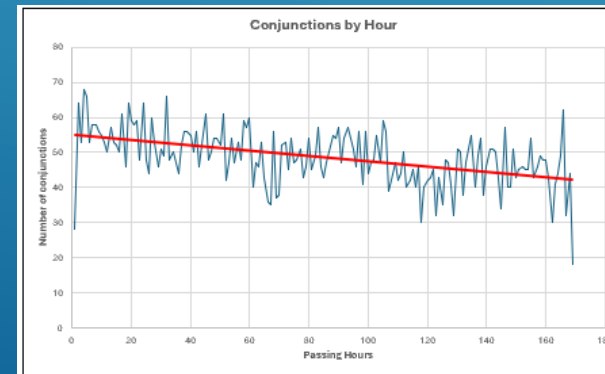
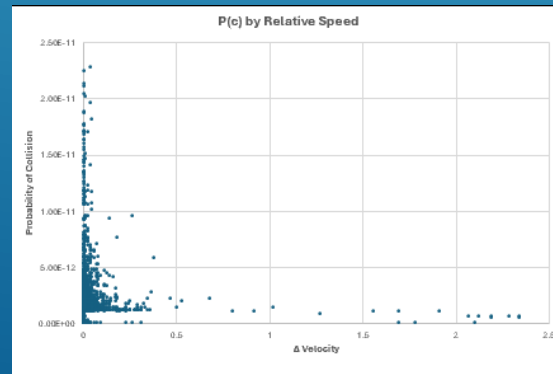
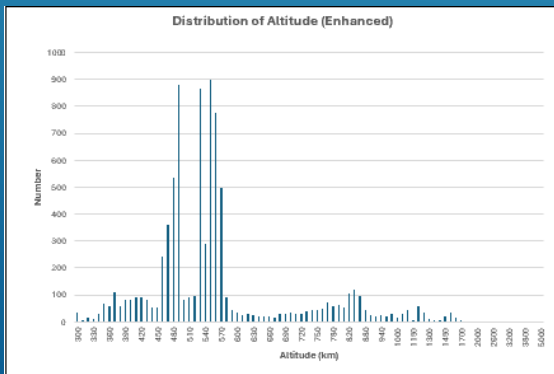
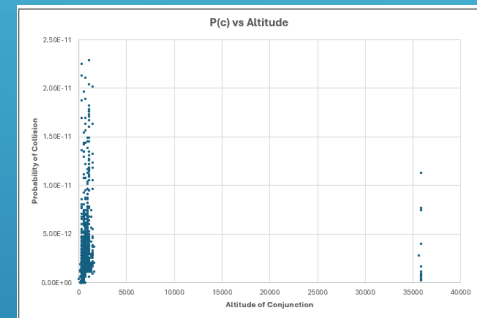
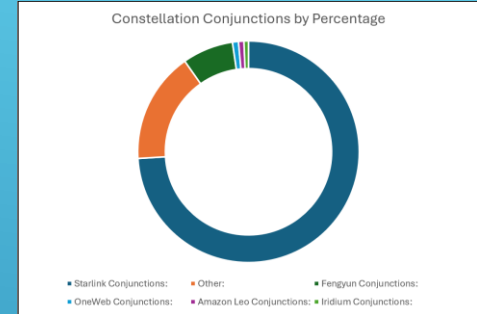
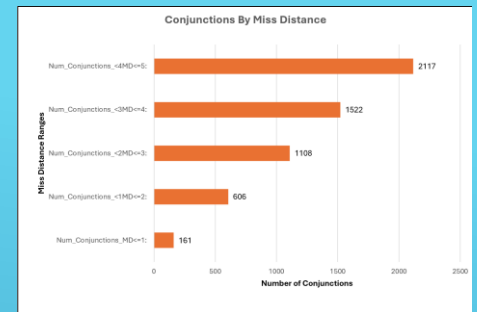
PyCharm. Credit:
<https://lp.jetbrains.com/pycharm-for-students/>



Credit:
https://www.linkedin.com/posts/comspoc_have-you-checked-out-comspocs-new-spacebook-activity-7249429953748811776-CaTn

RESULTS

- ▶ The chances of collision are extremely low, most commonly appearing between 1×10^{-11} and $1 * 10^{-13}$. However, thousands of conjunction events were reported, placing the expected number of collisions in one day about 7.45×10^{-9}
- ▶ Of these conjunctions, the vast majority were in LEO, at altitudes considerably less than 5,000 kilometers, but there was also a mode at approximately 35,000 kilometers, in geosynchronous orbit there were several as well.
- ▶ More conjunctions appeared the higher the miss distance was, likely caused by the small nature of satellites and the fact that larger miss distances are more probable due to higher area to conjoin with.
- ▶ Starlink as a constellation caused most of the conjunctions that were reported, with a total of 74.039% resulting from one or more Starlink satellites.



Credits: All graphs on this slide were created by the student in Excel.

DISCUSSION

- ▶ While almost all conjunctions were caused by Starlink, 83.796% of these were actually between Starlink satellites instead of Starlink interfering with others. While this is all well and good, a Starlink-Starlink collision is still a collision that creates many small debris particles, which can hit other satellites, causing similar damage.
- ▶ Starlink is not unaware of this issue, and their satellites are able to take collision avoidance maneuvers if the probability of collision ever gets too high. This threshold is relatively low, so: "... [SpaceX's] Starlink satellites between December 2024 and May 2025 performed 144,404 collision avoidance maneuvers" (O'Callaghan, 2025).
- ▶ Despite what seems like good news, it is important not to forget that Starlink launches most of its satellites into the same few altitudes, so those altitudes become very difficult for other satellites or constellations to occupy. Most satellites operate at about 550 km in altitude (Pultarova, 2025). There are thousands of these satellites flying at the same altitude. This is a recipe for disaster and further action needs to be taken to avoid a catastrophic scenario in the near future.
- ▶ This has happened before. On February 10, 2009, defunct Russian satellite Kosmos 2251 collided head-on with Iridium-33, an active satellite maintained by the US (NASA, 2009). While 17 years ago, this collision was truly catastrophic, spraying out a debris field of thousands of objects, many of which are unable to be tracked and may cause damage of their own. It only takes a few collisions to create a cascading effect, which may trigger Kessler Syndrome. The most chilling thing about it is that the satellites were expected to miss by 584 meters (2009 satellite collision, 2020). As COMSPOC's Chief Scientist Dan Oltrogge said, "Such an estimate provides an extremely small chance of a collision. About 10 to minus 34. But when we included [updated data] into our model, the probability increased to over 1 in 1,000, which is a very high number" (Avoiding Orbital Mayhem – Royal Aeronautical Society, 2023). Indeed, it is. That is over an order of magnitude higher than the risk threshold NASA considers to be threatening.
 - ▶ This problem will only be exacerbated by Starlink. In 2009, there was not a single Starlink satellite in orbit. In 2026, there are over 9,000 and by 2033, there are supposed to be 42,000 (Fox, 2019).



Debris fields of the high-profile collision between Iridium-33 and Kosmos 2251 Credit: https://en.wikipedia.org/wiki/2009_satellite_collision

SOURCES

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