Analysis of Space Debris Risk to Satellites in Low Earth Orbit

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ABSTRACT

With space traffic expected to grow significantly over the coming years, we must optimize ways to analyze satellite risk exposure to collisions with space debris and take actions to mitigate that risk. A space data collection and debris removal micro-satellite is used to conduct Rendezvous and Proximity Operations to detect and characterize potentially damaging 1cm to 10cm size debris objects. The satellite offers the option to remove those risky objects from orbit, saving customers valuable resources.
Methodological approach: Utilizing a standing agreement with the US Space Force, the team accessed Space Surveillance Data via Space-Track.org APIs including the Satellite Catalog for cataloged satellites, debris, and analyst satellite objects. The team scaled up the existing catalog of debris from roughly 10K objects to 40K synthetic objects and even 1M synthetic objects. A computer program simulated trajectories of the real and synthetic objects and calculated closest approaches to real satellites of interest with small time intervals. The simulation uses parallel computing using the python language. Main novelties of this work are the combined use of efficient algorithms, parallelization, and synthetic population generation.
Simulation results confirm that increase in space object population will decrease the distances between space objects dramatically. This technology can be used to inform governmental and commercial customers about the risk they face to collide with lethal/non-trackable debris in Low Earth Orbit.

ABOUT THE AUTHORS

Joseph Guzman is a 26-year Veteran of the US Army with over 18 years of Defense Space Operations experience and 23 years of overall space industry experience. Guzman founded Space Cowboy ADR in November of 2022 after completing work on a Department of the Air Force Small Business Technology Transfer (STTR) Phase I Contract to conduct a technical feasibility study and to develop a commercialization strategy for a space debris risk reduction capability. His team designed a patent pending space debris capture mechanism, an initial host satellite bus, and a business plan to provide Active Debris Remediation (ADR) and small debris data collection as a service. Joe holds a Bachelor of Science in Electrical Engineering from the United States Military Academy at West Point, a Master of Science in Space Systems Operations Management from Webster University, and a Master of Arts in National Security Strategic Studies from the United States Naval War College. Guzman is a retired Colonel and has been awarded the Defense Superior Service Medal, Legion of Merit, Bronze Star Medal, and the Army Master Space Operations Badge

Jacob Barhak specializes in chronic disease modeling with emphasis on using computational technological solutions. Dr. Barhak has diverse international background in engineering and computing science. He received his Ph.D. in 2003 from the Technion Israel Institute of Technology. From 2003 to 2006 he worked at an NSF Engineering Research Center at the University of Michigan focusing on inspection systems and personalization. From 2006 to 2012 he worked on developing disease modeling tools for the Michigan model for diabetes at the University of Michigan. The Reference Model for disease progression was independently self-developed by Dr. Barhak in 2012. He is active in the python community and is an organizer of the Austin python meetup.

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INTRODUCTION

Relatively little data exists about the precise orbital locations of "medium-sized" space debris. Satellite owner/operators accept the risk of space debris collisions mainly because: 1) Even when satellite/debris conjunctions are predicted, probabilities of collision are often perceived to be low. 2) Aside from conducting costly Collision Avoidance Maneuvers (CAM), no viable alternatives exist.

The solution discussed in this paper addresses the need for Active Debris Remediation (ADR). It is important to note that ADR has never been physically attempted before, so the task is difficult from scientific and practical aspects. The technology is patent pending (Guzman et al, US Patent Application).

The idea is to employ a fleet of micro-satellites, each about the size of 1m x 0.5m x 0.5m, to detect, characterize, and capture 1 to 10 cm-sized debris fragments in Low Earth Orbit (LEO), between 400 and 1200 km distance above the surface of the Earth. The LEO population of this size of debris numbers approximately 1.2 Million pieces according to the European Space Agency's 2024 Space Environmental Report (ESA SOC 2024, Online). Furthermore, 1 to 10 cm-sized debris, is commonly referred to by Space sustainability experts as "Lethal/Non-Trackable" (LNT) because it carries enough kinetic energy to significantly damage or destroy operational spacecraft and its small size is extremely difficult to consistently track using Earth-based sensors (NASA Orbital Debris Program Office: Radar Measurements, Online). The micro-satellite maneuvers into close proximity with debris to sense and collect high-accuracy data. This data is used to calculate orbital determinations for the debris that enable the system to capture these debris objects and relocate/de-orbit them using Rendezvous and Proximity Operations (RPO) (Space Engineering Research Center, Rendezvous and Proximity Operations (RPO), Online).

The video in (space data collection and debris removal micro-satellite on Vimeo, Online) and Figure 1 illustrate the space data collection and debris removal satellite during an ADR operation. The sensor package collects high-accuracy positional data and characterizes the debris object. Positional data is used to calculate satellite maneuvers to position the satellite's capture and arrest mechanism around the debris object. The mechanism then closes and stores the debris that is effectively removed from orbit and no longer can pose as a potential threat. The debris then is put into an assisted de-orbit by the satellite towards incineration by the atmosphere. In the future, recycling options may be possible, yet it is out of the scope of this paper. The space data collection and debris removal satellite will meet scalability and logistical requirements through the use of in-space services such as refueling, provided by commercial companies such as OrbitFab (OrbitFab, Online).

Because LNTs cannot be cataloged, satellites operate at risk of collision with them. Some expect the population of satellites to increase by 10X, reaching over 100,000 by 2030 (Scharping, 2021), (Aglietti, 2025), exacerbating the risk. We are therefore developing a risk assessment tool to aid in better illustrating the risk environment in LEO. The data will also be analyzed to position micro-satellite assets such that they can efficiently and effectively reduce debris collision risk for customers. According to 'Space debris by the numbers,' (Space debris by the numbers, online) the estimated number of break-ups, explosions, collisions, or anomalous events resulting in fragmentation is over 650 at the time this paper was written. One example is documented in the article, 'Space junk slams into International Space Station, leaving Hole in robotic arm' (Lewis, 2021) where a debris object damaged the arm of the international space station. Yet, there are many such collisions of which the public is not aware that should be addressed.

There are many aspects of developing such a system to succeed in its mission of removing space objects. This paper focuses only on improving upon the computational analysis of possible collisions with space debris by providing a computational solution.

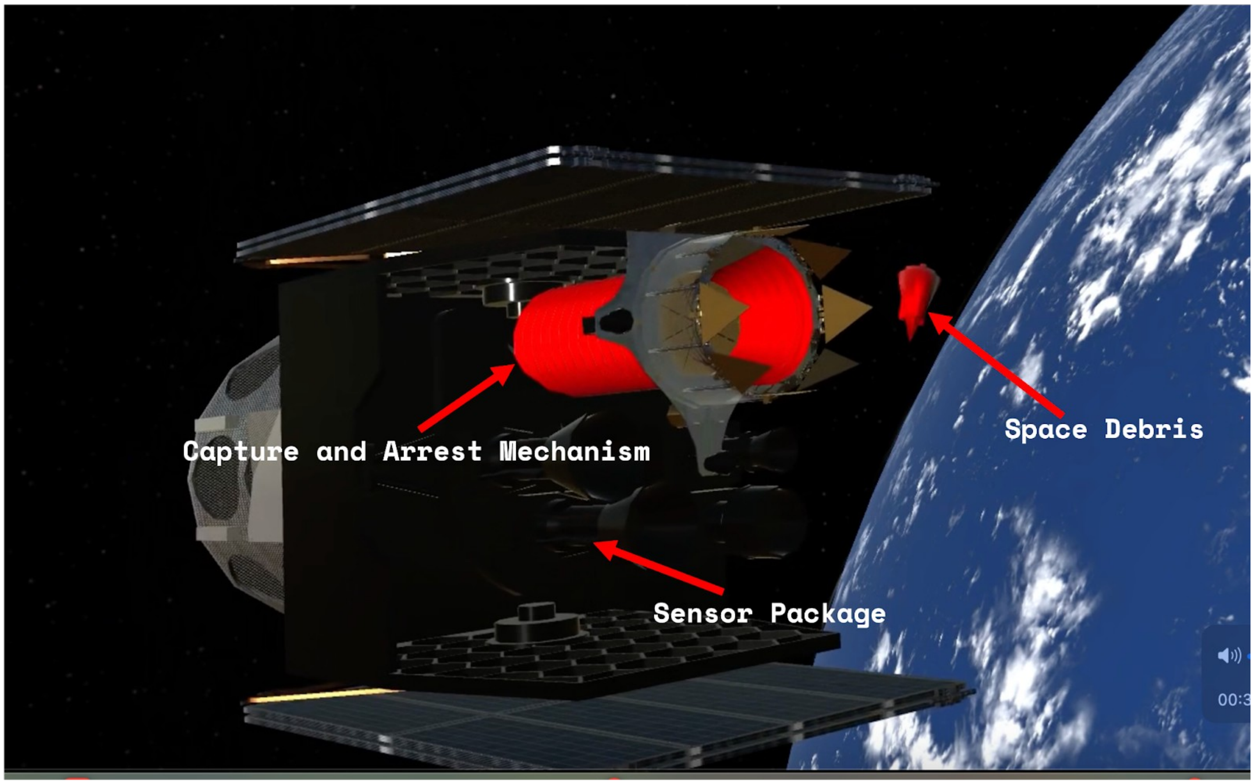

FIGURE 1. SPACE DATA COLLECTION AND DEBRIS REMOVAL MICRO-SATELLITE DURING AN ADR OPERATION

COMPUTATION SOLUTION FOR COLLISION DETECTION

Since not all debris are registered and traceable, we require a novel risk assessment solution based on following steps:

- Create synthetic satellites that represent pieces of lethal, non-trackable medium-sized debris in a similar distribution as tracked objects.
- Propagate the satellites, creating ephemerides for the next 24 hours
- Predict close approaches over the next 24 hours at a chosen time interval

Our Hypotheses are:

- **Hypothesis 1**: close approach incidents occur more often with the addition of synthetic satellite data
- **Hypothesis 2**: some orbital inclinations will have orbital debris populations that tend to impact more operational customers.

In this work, we address the first hypothesis.

Our main data source: US Space Force public facing website, (US Space Force. Space-Track.org, online). More specifically we use the US Space Force Satellite Catalog (SATCAT) (Kayhan Space, Online). This data is provided as Satellite time stamped locations and orbital data - 3-line Element Sets (3LE) (Two-line element set. Wikipedia, Online).
To calculate possible collisions, we use an orbit propagator, which forecasts time-stepped satellite location (ephemeris) in the future. We compare satellite locations at each time step and calculate the distance between

objects. When that distance violates a set threshold, it is categorized as a "close approach." Figure 2 shows the Pseudocode of the collision detection algorithm.

```
Collision Detection Algorithm Pseudocode:
    1    Load Satellite data
    2    Generate fake Satellites to simulate the future congestion in space
    3    For each time step T
         3.1  For each object
              3.1.1Propagate the object to calculate its position in space
         3.2  Filter miscalculated objects
         3.3  Calculate nearest neighbors and their miss distances for each object
    4    Generate final report
```

FIGURE 2. COLLISION DETECTION ALGORITHM PSEUDO CODE

Algorithm Analysis

The pseudocode in figure 2 does not address the real difficulties in such an algorithm. If the algorithm were executed on a single CPU core serially while trying to compute all the nearest neighbors, the complexity of finding the distance between N objects in T time steps is $O(N^2T)$. This is highly inefficient since for 1M LNT we estimate the computation will take 10,000 more times than computing the ~10k TLEs currently listed. This kind of scaling is impractical. Moreover, it does not take into account the great advances in computer architecture and software that allow easy parallelization.

To improve computation time we employ techniques like k-d tree (scikit-learn kd tree, Online) used frequently in machine learning and computational graphics to calculate nearest neighbors. This way objects that are far apart at a certain time step are excluded from computation and only the k nearest neighbors are computed. In a k-d tree, space is separated by hyperplanes for each dimension, in our case, x,y,z that separates space into regions that are easily accessible to determine nearest neighbors. We are using the scikit-learn library to get great speedup to a complexity of O(N*logN*T). So computing 1M objects compared to 1K objects will only cause an increase of roughly hundreds compared to the brute force approach. Other possible solutions for fast nearest neighbor search are ball trees (scikit-learn BallTree, Online) and Hierarchical navigable small world (Hierarchical navigable small world, Online) abbreviated as HNSW. We chose k-d tree because in our case the dimension d is 3 since we only use x,y,z, coordinates and this will not increase. Therefore, the algorithm is very efficient - k-d tree is known to lose effectiveness in large dimensions; however, since dimensions are limited in our case, the algorithm is a good choice.

However, we notice that propagation steps calculated by the Skyfield Python library (skyfield, Online) are independent since the propagation time is one of the arguments we pass to the propagation function. So each time step we compute for all nearest neighbors can be potentially calculated on a different compute core. In essence, it is an embarrassingly parallel algorithm. So if we have M compute cores we can employ we can reach a complexity of O(N*logN*T/M). Since computing power has become so cheap and parallelization tools are easily available, this can easily do additional linear acceleration with minimal effort without complex algorithmic speedup.
We chose the Python Dask (dask, Online) framework for orchestrating the parallel computations since it has been used before for complex disease modeling (Barhak, 2021).

One technical challenge while scaling computation is that there is an overhead associated with parallelization. To reduce the overhead, not every time step was parallelized. Instead batches of 250 time steps were executed serially so that there will be less overhead associated with maintaining many parallel processes. Since there is a limited number of computing cores, there is no reason to launch too many parallel processes since this demands more compute resources such as more memory to maintain all those parallel processes together. However, if there are sufficient compute cores and memory, then batch size of 1 is possible and will save computation time. However, when scaling to hundreds of CPU cores or more requires sending information over different compute nodes that may create an I/O bottleneck. Nevertheless, the balance obtained in this work allowed getting results in reasonable time on a modern desktop PC and was satisfactory.

Note that the application of parallel computing for disease models and for satellites are not very different. In both cases, a synthetic population is generated and then propagated through time. With disease models, complex techniques are used for generating synthetic data. In the satellite case, very simple perturbations of existing satellites are used to calculate new space objects that simulate the undetected space debris. To generate new synthetic satellites, we perturbed the following attributes of each real satellite: orbit inclination, right ascension of ascending node, eccentricity, argument of perigee, mean anomaly, mean motion, and revolution number at epoch. Minor perturbation to those elements and creation of multiple synthetic perturbed copies creates sufficient number of satellites that generally mimics the existing distribution of satellites that we track today while providing variability that attempts to estimate a possible future distribution. Our assumption is that tracked debris represent the distribution of non-tracked debris.

RESULTS

The algorithm was implemented in Python and executed on a computer with AMD Ryzen™ 7 5700G 8-Core, 16-Thread Desktop with 64Mb RAM. Simulation included 3 runs of roughly 10K, 40K and 1M orbital objects that were generated from 1 TLE report.

Our reporting system allows focusing on specific satellites to reduce the focus on collision. After all, we are targeting this service at customers we can focus on. Table 1 shows the results of the runs.

Note that the runs are not associated with each other; the first run does not include any synthetically generated satellites, so distances between satellites are actual to the time period calculated. The other scenarios include synthetically generated satellites that are indicated by starting their name with the word 'Fake' followed by a number and the original satellite that they used as a base for perturbation to calculate the new orbit. In these situations, only a very simple perturbation strategy was applied to generate synthetic satellites.

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For brevity we only show the single closest object to the satellites of interest in the table. In all these runs we actually provide a list of 200 closest objects to the satellites chosen in focus. for the entire time span. Note that those are selected from 20 closest objects calculated for each time step. The closest encounter also indicates the time and positions of both objects. Figure 3 shows the results of the two closest encounters for the 40K simulation. One can clearly see that the second closest object is a real satellite detected in the 10K run to be closest. The 40K run just includes more satellites that did not exist in the 10K run and this results in a closer distance passing being detected. The more objects we have, the more chances of collisions exist. Figure 4 shows the closest 200 distances for the 3 simulations.

TABLE 1. RESULTS SUMMARY

	Actual SATCAT	Actual SATCAT+ 3 Synthetic Objects per Satellite	SATCAT + 99 Synthetic Objects per Satellite
Number of Objects	10828	10828	10828
Total Number of Objects	10828 (10K)	43312 (40K)	1082800 (1M)
Satellites in Focus	IKONOS 2, ISS (ZARYA)	IKONOS 2, ISS (ZARYA)	IKONOS 2, ISS (ZARYA)
Date	21/09/2024	21/09/2024	21/09/2024
Time Interval	10 sec	10 sec	10 sec
Time Steps	8000	8000	8000
Closest Distance	11.25km	10.17km	1.46km
Calculation time	~16 min	~1hr	~7 hours
Closest Object	IKONOS 2 - STARLINK-3077	IKONOS 2 - FAKE39169LEMUR 2 OBA-NI-	ISS (ZARYA)- FAKE492549FLOCK 4X 32

One can see clearly that the closest debris to the satellites in focus is much closer for the 1M simulation than the 10K simulation. However, it's important to comprehend that the closest object to a satellite of interest is only a sample of a larger distribution function. Just like a person with a very high heart rate does not indicate that the entire population of people in a state is at risk. Nevertheless, we are looking for high-risk events that are rare, so just like locating a person with a very high heart rate in a population and recommending a treatment may save a life, locating a possible close encounter of very low distance and dispatching a satellite to remove a threat may prevent a collision. Although the satellites we simulate may be synthetic, when we increase the number of synthetic satellites dramatically we clearly see the effect of increasing the population size - in Figure 4, when examining the closest 200 encounters, we observe that in the 1M scenario, there are 171 encounters closer than the closest encounter in the 10K scenario. The 172nd closest encounter in the 1M scenario is the closest encounter in the 10K scenario.

For additional details in video form, please visit (Barhak and Guzman, Online). All simulations were computed in reasonable time. This supports our first hypothesis.

```
"10.171623113336189": [
      {
         "time": "2024-09-21T10:09:20+00:00",
         "object_id1": 1402,
         "object_id2": 39169,
         "object_name1": "IKONOS 2",
         "object_name2": "FAKE39169LEMUR 2 OBA-NI-",
         "object_pos1": [
            -898.5231428625193,
            -469.87716720841416,
            -6904.313122957741
         ],
         "object_pos2": [
            -904.612637955789,
            -475.2852907064028,
            -6910.406739822896
         ]
      }
   ],
   "11.25270633327094": [
      {
         "time": "2024-09-21T11:03:10+00:00",
         "object_id1": 1402,
         "object_id2": 4460,
         "object_name1": "IKONOS 2",
         "object_name2": "STARLINK-3077",
         "object_pos1": [
            1908.9450621075678,
            -1783.7878769494678,
            6445.5482133490505
         ],
         "object_pos2": [
            1903.2894596088056,
            -1785.106123271492,
            6435.909759799165
         ]
      }
   ],
...
...
```


FIGURE 3. TWO CLOSEST OBJECTS FOR THE 40K SCENARIO

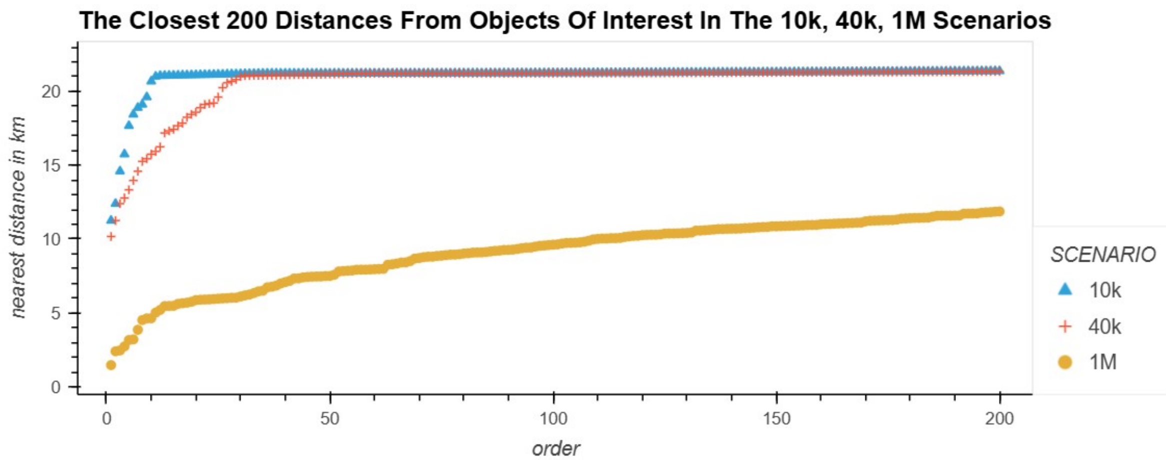

FIGURE 4. THE CLOSEST 200 DISTANCES FROM OBJECTS OF INTEREST IN THE 10K, 40K, 1M SCENARIOS

CONCLUSIONS

In this work our preliminary results have shown that the first hypothesis is correct i.e., that close approach incidents occur more often with the addition of synthetic satellite data. We can also speculate that the danger for objects in space will increase dramatically because:

- Many non-tracked objects exist already
- Each collision can create new debris objects
- Many objects are launched from Earth

Since the increase in objects will increase the chance of collision, there is a need for handling space objects; therefore, we conclude that ADR operations may already be necessary and as our simulations show that the clutter in space will become much worse. Wed can easily run simulations larger than 1M satellites and see implications by using multiple compute nodes with more cores to compute results in reasonable time, i.e., compute what may happen in a day away in a few hours. As the number of objects in space increases, we may need such computations. Fortunately, simple parallelization is possible in this case without significant changes to the work presented here.

However, the second hypothesis has not been properly addressed in this work. This hypothesis is important to address because it will determine initial launch parameters for the space data collection and debris removal micro-satellite. For this hypothesis to be addressed more, data needs to be collected and analyzed. Future work towards this direction has already been plotted and includes elements such as:

- Continuous integration with Space-Track.org for TLE extraction
- Overlapping simulations with multiple results per time step
- Archiving simulation results for a database
- Analyzing results towards validating hypothesis 2

Future work will therefore help improve our understanding of space debris distributions towards determining launch parameters. Orbital inclination refers to the angle between the plane of an object's orbit and a specific reference plane, typically the equatorial plane of the celestial body it is orbiting. It essentially measures the "tilt" of an orbit. This angle is measured at the ascending node, which is the point where the satellite's path crosses the equator while moving from south to north.

For a "chaser satellite" to successfully perform rendezvous and proximity operations with a piece of debris, it must precisely match the debris' orbital trajectory, including its plane, altitude, and phasing. Matching the orbital inclination is paramount because it ensures that both the chaser and the debris are operating within the same orbital plane. Without this co-planarity, the two objects would continuously cross paths at different angles, making a close approach or any form of controlled interaction impossible. Imagine trying to shake hands with someone running on a different track that crosses yours at an angle – it's incredibly difficult to achieve a stable connection. In space, where relative velocities are immense, even a slight difference in inclination means the objects are on fundamentally different paths, preventing the precise station-keeping required for proximity operations or eventual docking/capture.

While essential for rendezvous and proximity, inclination changes are among the most "expensive" orbital maneuvers in terms of the required change in velocity and, consequently, propellant consumption. This is why mission planners typically try to launch spacecraft as close as possible to their desired inclination to minimize the need for such maneuvers throughout the mission's life. By positioning future ADR assets in orbital inclinations replete with particularly harmful debris objects, ADR operations become more efficient, more affordable, and more valuable to customers. Our simulation work would help with this in future research.

Other work will focus on improving the synthetic population generation and compare it with ORDEM 3.2 : OD Engineering Model (NASA Orbital Debris Program Office, ORDEM 3.2, Online). We acknowledge that there may be differences between the synthetic LNT debris population model and a truly representative model of the actual uncataloged LNT population. One possible path of research is the synthetic generation of satellites that would potentially mimic events such as debris from collisions or other events that affect the space population. Another possible research path is focusing on mechanics of the synthetic population, such as including orbit constraints. Another path to explore is creating scenarios that test the assumption that tracked satellites represent the non-tracked debris population.

However, our work here demonstrates the feasibility of timely and efficient collision predictions with significantly increased operational satellite and debris populations. We fully expect capabilities like those provided by our solution will be necessary for long-term space environmental sustainability (NASA Space Sustainability Strategy, Online) and the expansion of space-based economic activity that benefits all of humanity. However, it is important to note that there are many non-trackable objects that exist already today- estimated over 1M (1cm to 10cm in size) or even 140M (1mm to 1cm in size). So many collision events cannot be forecasted or detected using today's equipment. The in-space tracking that the proposed satellite will provide will allow the forecast of potential collisions that are impossible today. In this paper we limit our simulations to 1M since we are looking at the potential benefit that the solution will provide today. However, as explained before space activity will increase those numbers in the future. Fortunately, our solution can be easily scaled through parallelization.

ACKNOWLEDGEMENTS

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CONFLICT OF INTEREST STATEMENT

Joseph Guzman is the CEO of Space Cowboy that intends to use the technology in this paper for commercial purposes and intends to profit from this technology.
Jacob Barhak is a sole proprietor that intends to profit from the technology developed for this paper in a future arrangement with Space Cowboy. You can find other commercial and financial interests in this url: https://sites.google.com/view/jacob-barhak/disclosures .

REPRODUCIBILITY

The simulations and results for this paper are archived in the files space_2024_09_28_10k.zip, space_2024_09_28_40k.zip, space_2024_09_28_1M.zip. The software environment was Winodws 11 Pro. Python 3.11.9. scikit-learn1.5.1., skyfield 1.49, dask 2024.8.2.

REFERENCES

Aglietti, G. S. (2025, June 25). *From space debris to Neo, some of the major challenges for the space sector*. Frontiers. https://www.frontiersin.org/journals/space-technologies/articles/10.3389/frspt.2020.00002/full https://doi.org/10.3389/frspt.2020.00002

Balltree. scikit. (n.d.-a). https://scikit-learn.org/stable/modules/generated/sklearn.neighbors.BallTree.html

Barhak, J. (2021, June 23). How Dask Helped Model Diseases and Specifically COVID-19. *Coiled.com*. June 24, 2025, https://coiled.io/how-dask-helped-model-diseases-and-specifically-covid-1921

Barhak, J., & Guzman, J. (n.d.). *A Space Debris Risk Analysis Tool*. YouTube. https://www.youtube.com/live/rh8M90OztTM?si=7pfXRA1S9gNNIZFZ&t=1890

Dask. (n.d.). https://www.dask.org/

ESA ESOC. (2024). (rep.). *ESA's Annual Space Environment Report 2024* (pp. 3–8). Darmstadt, Germany. https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2024

Guzman, J. (n.d.-b). *Space Data Collection and Debris Removal Micro-satellite*. *Space Cowboy*. Space Cowboy ADR. Retrieved June 24, 2025, Vimeo, Online: https://vimeo.com/1085830139

Guzman, J., Rose, R., Rose, T., Lyons, T., & Porter, C. (n.d.). System and Method for Capturing Space Debris.

Kayhan Space. (n.d.). *Spaceflight Intelligence Exchange*. Satcat. https://www.satcat.com/

KDTree. scikit. (n.d.-b). https://scikit-learn.org/stable/modules/generated/sklearn.neighbors.KDTree.html

Lewis, S. (2021, June 2). *Space junk slams into International Space Station, leaving Hole in robotic arm*. CBS News. https://www.cbsnews.com/news/space-junk-damage-international-space-station/

NASA Astromaterials Research and Exploration Science (ARES). (n.d.). *Radar Measurements*. NASA Orbital Debris Program Office. https://orbitaldebris.jsc.nasa.gov/measurements/radar.html

NASA. (2024, May 28). *NASA's Space Sustainability Strategy*. NASA. https://www.nasa.gov/spacesustainability/

NASA. (n.d.). *Ares*. NASA. https://orbitaldebris.jsc.nasa.gov/modeling/ordem.html

Orbit Fab. (2025, March 3). http://www.orbitfab.com/

Scharping, N. (2021). The Future of Satellites Lies in the Constellations. *Astronomy*. https://www.astronomy.com/space-exploration/the-future-of-satellites-lies-in-the-constellations/

Skyfield . Skyfield - documentation. (n.d.). https://rhodesmill.org/skyfield/

Space debris by the numbers. ESA. (n.d.). https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers

Space Engineering Research Center. (n.d.). Rendezvous and Proximity Operations (RPO). https://www.isi.edu/centers-serc/research/rendezvous-and-proximity-operations-rpo/

US Space Force. (n.d.). *Space-track*. Space-track.org. https://www.space-track.org/

Wikimedia Foundation. (2025a, June 6). *Hierarchical Navigable Small World*. Wikipedia. https://en.wikipedia.org/wiki/Hierarchical_navigable_small_world

Wikimedia Foundation. (2025b, June 18). *Two-line element set*. Wikipedia. https://en.wikipedia.org/wiki/Two-line_element_set