Agent-Based Modelling of Kessler Syndrome and Debris Removal Techniques

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The number of objects in low earth orbit (LEO) continues to increase. As satellite density increases, risk of collisional cascading (sometimes known as Kessler effect) increases dramatically. This paper presents an agent-based model suitable for examining how debris load in LEO will evolve over time. The model is used to explore a variety of satellite launch rate assumptions and different cleaning techniques. The effects of these choices on risks to satellites and rocket launches through LEO are examined.

I. Motivation and Background

A. Motivation

In 1978, Donald Kessler published a seminal paper discussing the effects of continued satellite launches on earth orbits. In it, Kessler proposed that over time, satellites could collide with each other and produce many fragments, eventually creating an orbital debris belt [1].

Forty years later, it is clear that Kessler was prescient in his concerns. The amount of debris in orbit has increased dramatically, and in 2009 the first collision between orbiting satellites, the Iridium-Cosmos collision, was observed. The Iridium-Cosmos collision resulted in 1632 tracked fragments, many of which will remain in orbit for decades. It is expected that many objects too small to track, but still dangerous to satellites, were also generated in this collision [2]. Even without collisions between satellites, other human actions can create large amounts of debris. For example, an Indian anti-satellite weapon test recently created approximately 400 pieces of debris, 60 of which are large enough to be tracked by NASA [3].

As the amount of satellites in the atmosphere increases and the debris load of LEO increases, events like the Iridium-Cosmos collision are likely to become more frequent. Over time, this poses a serious threat to the continued use of LEO, and potentially a threat to launches that pass through LEO. Already, satellites in low-earth orbit are sometimes required to take action to avoid collisions with debris. From 2000 to 2015, the ISS needed to maneuver 25 times to avoid collisions with space debris that could have caused damage to the structure and injury or death to the astronauts within [4]. If LEO debris load were to become significantly larger, it is possible the ISS would become unsafe for further operation.

Apart from its effects on the ISS, the effects of an increased debris load in LEO will have many other detrimental effects on modern life. From GPS to telecommunications, many facets of our lives are improved through effective use of orbital devices. In order to preserve the benefits of these systems, the Kessler effect must be better understood and actions to prevent it must be undertaken.

Many suggestions on how debris can be eliminated from the atmosphere exist. Suggestions range from satellite-based netting methods [5], to using maneuverable spacecraft with robotic arms to place rocket engines on large pieces of debris [6], to using a ground-based laser system (laser broom) to lower the perigee of debris and cause it to burn up in the atmosphere [7]. A review of many proposals of interest is available in [8].

In order to make effective design decisions on which of these debris removal strategies are adopted, the effects of the proposals on debris populations in LEO over time must be understood. The remainder of this paper presents an agent-based model suitable for analyzing these effects, and exercises the model to examine selected debris removal proposals.

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II. Methodology and Simulation Details

A. Agent-Based Modelling

In order to capture the interactions between different debris removal systems and the existing debris load, an agent-based model was used. Agent-based modelling characterizes a system through the use of a large number of "agents", each of which follows a known set of rules. Despite the known rule set, the interactions between agents can quickly lead to complex and interesting results. Known as emergent behavior, these results can reveal important effects that would be difficult to detect using other analytical methods. Conway's game of Life, for example, is an agent-based model with only four rules that nevertheless can create complicated and interesting ecosystems [9]. A wide variety of resources are available for readers interested in more detail on agent-based models [10, 11].

B. Model Mechanics

In this model, objects orbiting the earth are treated as agents. Each agent is subjected to the simulation rules described in the flowchart shown as Figure 1. Five types of agents are considered in the model. They are:

- Derelict satellites.
- Clouds of smaller space debris.
- Active satellites.
- Debris removal satellites. Debris removal satellites capture and deorbit larger derelicts or debris objects using nets, boosters, harpoons, or tentacles.
- Ground-based laser debris removal systems (laser brooms). Ground-based laser systems are complex, and rely on being able to ablate a small portion of a piece of debris to provide it with an orbit-altering thrust. These changes in orbit will, over a short period of time, cause the debris to fall into the atmosphere and deorbit (more information is available in [7]).

Each agent has characteristic actions which it takes when it finds itself closer than its critical difference to another agent. Derelict satellites, for instance, will crash into each other and debris clouds, creating a larger number of debris clouds. Active satellites will avoid other agents. Debris removal satellites will, depending on the experiment, remove derelict satellites and perhaps debris clouds within 5 km of their orbital path. Ground-based laser systems periodically remove both derelict satellites and debris clouds within their line of sight (50 degrees of rotation around a point on the surface of the earth).

As Figure 1 shows, satellites move once per tick. For each movement, an acceleration vector is computed according to Cowell's Method [12]. This acceleration is numerically integrated to yield an updated velocity and position vector for each satellite. To balance model accuracy with available resources, a tick length of .05 seconds was selected.

C. Computational Costs

This model has required significant effort to reduce to a reasonable computational load. The model was originally programmed in Python, using object-orientation (each agent was an object). However, since object calls in Python are expensive, this yielded unacceptable performance speeds. Speeds were on the order of 3 seconds per tick.

In order to reduce the computational load, object-orientation was abandoned. Agents were generated into a matrix, each row of which contained the information for a single agent. It quickly became apparent that large amounts of vector algebra would be performed in this paradigm, so the model was ported to MATLAB.

Even with the reduced overhead of using matrices instead of objects, the model did not yield acceptable performance. Using a time profiler, it was shown that a disproportionate amount of time and memory was used to determine the distance between each object and all other objects each tick. To reduce this cost, a nearest-neighbor approach was adopted. Each time an object was examined, its distance to its nearest neighbor was recorded. Using this distance and a maximum speed for the orbits of interest, the shortest time before the object could collide with its nearest neighbor was calculated. Since the object could not collide with any object before that time, its distances to other objects were not calculated until then.

It also became apparent that computational costs vary with the square of the number of objects modelled (since each object must compute its distance to every other object). In order to reduce the number of objects modelled, it was assumed that smaller chunks of space debris tends to be clustered in clouds. This assumption was necessary to bring computational costs down to reasonable levels, and is discussed also in section II.D.

Using the cloud assumption and the nearest-neighbor approach, the computational power required for each iteration was reduced by approximately 1,000x. This brought the computation time down to around .0001 seconds per tick, a much

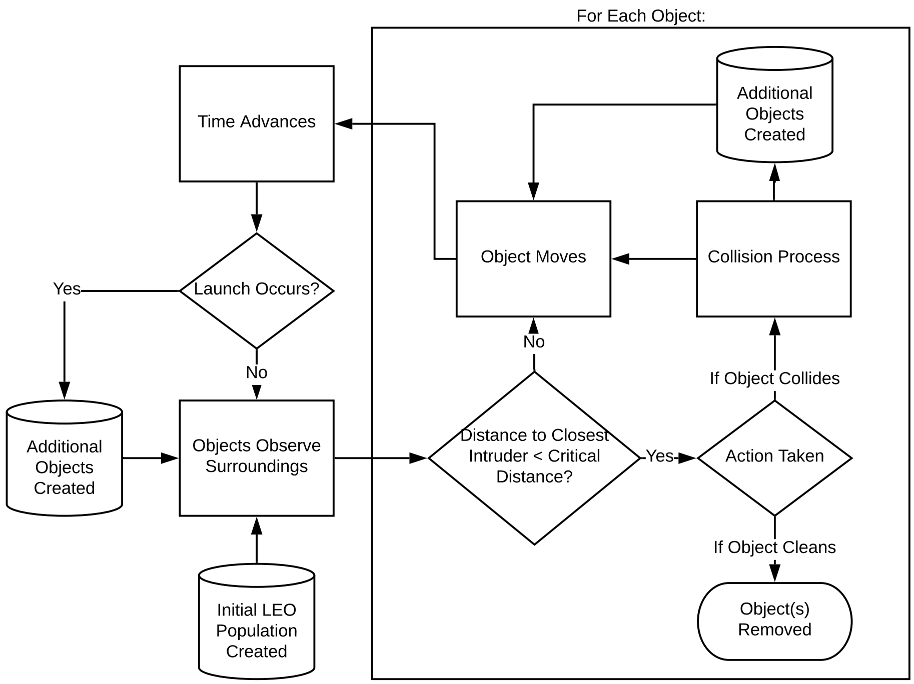

Fig. 1 Rules for each tick of the simulation. The section "Action Taken" depends on the types of both agents involved.

more reasonable value. This expense requires around 45 minutes to model a day in orbit to reasonable (approximately 350 meter) accuracy.

D. Key Assumptions

In order to bring computational costs down to reasonable levels, several assumptions were required. They are:

- Derelict satellites that pass within 100 meters of each other collide. With the current tick length, the model's resolution is only 350 meters. This assumption means that approximately 8% of satellites passing within the model resolution to each other will crash. This is likely to produce a pessimistic satellite collision rate.
- Small-diameter space debris is clustered in "clouds" 1,000 meters across. Objects passing through clouds have some probability of colliding with one of the objects within them. Although some space debris exists as solitary, small objects, there is reason to believe that for the majority of objects this cloud assumption is reasonable. When objects break up in the atmosphere, the debris generated generally maintains approximately the same path as its parent object. Furthermore, debris chunks with significantly different velocities than the parent object tend to de-orbit rapidly. Visualizations of the Iridium-Cosmos collision, available at `https://www.youtube.com/watch?v=_o7EKlqCE20`, are useful for understanding this behavior.
- Only a small shell of LEO (centered on 800 km) is modelled. Figure 2 gives context for this assumption.
- Highly elliptical orbits are not modelled.

Although these assumptions constrain the accuracy of the model, the model still generates results that are within expected values for cases where no debris removal methods are present. The model is imperfect, but is still capable of performing useful analysis.

E. Explorations

The focus of this paper is the effects of different debris removal solutions on risk to satellites in low-earth orbit. Accordingly, the inputs to the simulation are:

- Launch rate of additional active satellites (varying between two per day to one every 3.5 days); this brackets recent year's launch rates [14].

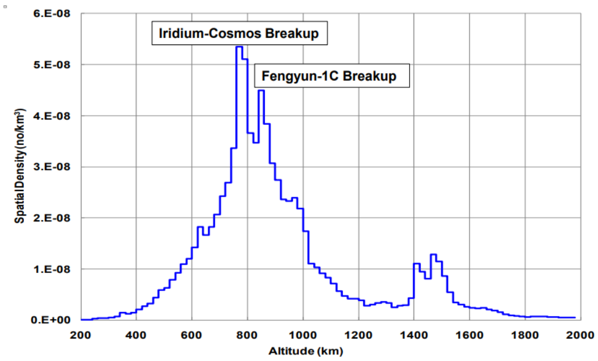

Fig. 2 Distribution of objects tracked by NASA in low earth orbit. Because Kessler effect is most pronounced at at high densities, 800 km was selected for use within the simulation. Taken from [13].

- Number of active cleaner satellites (varying between 0 and 3).
- Number of active laser brooms (varying between 0 and 1).
- Whether cleaner satellites destroy only defunct satellites, or also debris clouds.
- Simulation maximum run time.

The total number of cleaning solutions present was kept low, because it is considered unlikely that large numbers could be manufactured over the time scales considered. (Due to the computational costs of the model, simulation run times were limited to around 200 days). An orthogonal design of experiments was developed to test for the effects of each of these factors. This research was performed using MATLAB on resources provided by the Office of Research Computing at Brigham Young University. The design of experiments performed is attached as Appendix A.

The model output the following data:

- Density of objects in low earth orbit.
- A Poisson distribution describing the likelihood of n collisions occurring with an object the size of the ISS in the next year (as described in [15]).
- The likelihood of a collision occurring with a rocket as it passes through LEO.
- Number of each agent type in orbit at simulation end.
- The count of each type of agent interaction over the simulation time (number of laser shots, successful cleaning missions, etc.).

Since the density of objects in the atmosphere directly determines the collision likelihoods, discussion will focus on the effects of the inputs on densities. References to collisional likelihoods are given to provide a sense of scope to the discussion. Output is given several times per simulated day, so that results can be tracked over time.

III. Results and Discussion

Despite some uncertainty in end collision risks, the model demonstrates that different proposed solutions do have important effects on risk. Using a main effect screening linear fit model, the effects of the inputs on end density were examined. The model given here as figure 3. The regression shows that the presence of a laser broom has a dominating effect on the amount of junk in the atmosphere, with cleaner satellites following behind in importance (see figure 4). Whether cleaner satellites clean smaller debris is unimportant to end densities.

Laser brooms also outperform cleaner satellites when we examine collision prevention. The majority of collisions detected by the model were collisions between small debris chunks and derelict satellites, as would be expected. Regressing these collisions against the input variables (figures 5 and 6), it is clear that the presence of a laser broom is the most important factor.

Examining the data captured on interactions between different agents, the reasons for the laser broom's outperformance is clear. On average, cleaner satellites removed 12.25 objects per satellite. When present, the laser broom removed an average of 215 objects. Even with three cleaner satellites, the laser broom is simply able to interact with more debris than satellites are.

This effect is almost certainly due to the laser broom's huge range. While cleaner satellites must be within a few kilometers of a derelict to remove it, a laser broom can remove debris across a comparatively huge swath of sky (at the

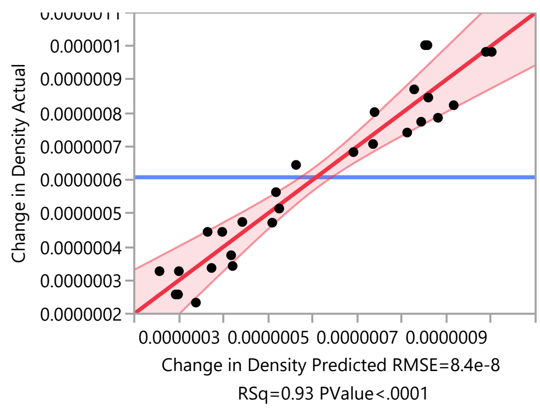

Fig. 3 Changes in object density in LEO over 203 days of simulation. Note that all changes are positive, meaning density increased in all cases. On the other hand, the magnitude of density change is highly dependent on the solution selected. The highest density change results in a 7% increase in risk to an ISS-sized region per year; the lowest results in an increase of only 3%.

Source	LogWorth	PValue
Laser Broom Presence	10.034	0.00000
Launch Rate(864000,6048000)	2.902	0.00125
Number of Cleaners	1.516	0.03045
Clean Clouds?	0.075	0.84071
Clean Clouds?*Number of Cleaners	0.063	0.86495

Fig. 4 A linear regression of the main input effects on end object density. At the .05 level, the number of cleaner satellites, the presence of a laser broom, and the launch rate of new satellites are all significant.

altitude considered, the affected area is approximately a circle 1000 km in radius). While the laser must cool down and aim between shots, the larger number of shots it is able to take dramatically increases its effectiveness.

Despite the laser broom's high level of performance, they are unlikely to be a panacea. To deorbit objects, laser brooms rely on being able to ablate a portion of that objects' surface. However, the ability of a laser to ablate material is dependent on many factors, many of which are out of control of the laser operator [7]. It is likely that some amount of debris will exist that a laser broom will be incapable of removing.

Another potential issue with laser brooms is the low level of thrust provided per pass overhead. For low-density, smaller debris, even the small thrusts available are sufficient to cause deorbiting in one pass overhead. For heavier objects, many passes may be necessary. For large derelicts, then, cleaner satellites may offer a faster and more attractive removal method.

Cleaner satellites also have an advantage in that they can be launched to target specific high-risk derelicts or debris objects. Laser brooms, on the other hand, must be built where terrestrial conditions permit, and must wait for debris to come to them. Certain objects (like the now-defunct Envisat) are both large and on dangerous courses [16]. A laser broom would take many passes, with significant time between passes, to deorbit Envisat. Total time to deorbit would likely be on the order of years. A cleaner satellite, however, could do it within days of launch.

Cleaner satellites also have an advantage in dealing with heavily-trafficked orbits. For a laser broom, having several large objects close to each other will increase the time taken to deorbit each one; the laser can only focus on one each time the group passes over it. For cleaner satellites, having large objects in close proximity would allow a single cleaner to target several derelicts with reasonable fuel costs, providing substantial advantages.

A. Limitations

Although the results from the simulation are valuable, the simulation has limitations. One area where the simulation may not be perfect is in modelling collisions between derelicts. In every situation considered, the risk to an international space station-sized region within the orbit considered increased by at least 3%. This is probably overstated; the number of satellite-on-satellite collisions recorded by the model is high compared to other reported values. The comparatively

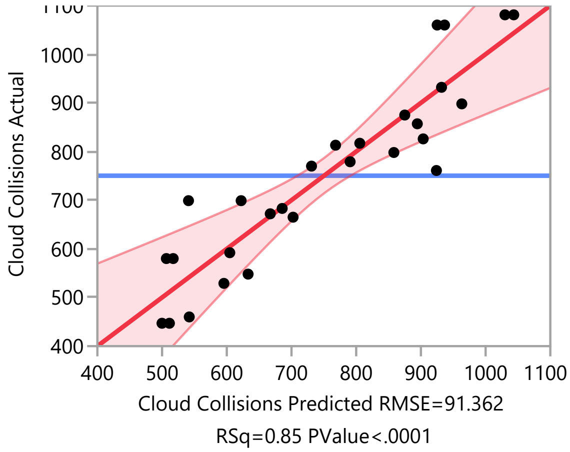

Fig. 5 Number of collisions between derelicts and smaller debris 203 days of simulation. Because satellite beginning locations are randomly seeded, the input variables do not explain all of the collisions. This results in a smaller r^2 value, and is to be expected.

Source	LogWorth	PValue
Laser Broom Presence	6.886	0.00000
Launch Rate(864000,6048000)	2.776	0.00167
Number of Cleaners	0.313	0.48622
Clean Clouds?*Number of Cleaners	0.107	0.78225
Clean Clouds?	0.072	0.84808

Fig. 6 A linear regression of the main input effects on collision. At the .05 level, only laser broom presence and launch rate had an important effect.

low resolution of the simulation, and the assumptions made to deal with it, likely contribute to this effect. The effects on risk of the input values are should not be affected by these flaws.

There is also reason to believe the simulation as it stands understates the laser broom's effectiveness. After a short time (on the order of days), the rate at which the broom removed debris plummeted. Investigation showed that the broom had largely depopulated the orbits that passed overhead. In the simulation, the rotation of the earth with respect to LEO had been neglected. Therefore, the laser broom remained focused on the same portion of the sky for its entire lifetime, and could affect only a small portion of the total space junk in the sky. In the real world, low-earth orbit is not geosynchronous, and so the field of derelict satellites and debris within the lasers' range would change over time. This would give the broom more targets to work on, and would allow it to remove objects at its characteristic high rate over a longer period of time.

IV. Conclusions

Agent-based simulation shows that in the short term, Kessler effect is likely to continue to degrade the usability of low earth orbit despite cleaning efforts. Nevertheless, cleaning efforts can significantly reduce the rate at which risks increase, with substantial effects over time. Of the cleaning solutions examined, ground-based laser systems were the most effective by an order of magnitude. However, situations may exist where other solutions, such as satellite-based removal systems for large derelicts, will also be effective.

A. Future Work

In order to provide a higher resolution understanding of Kessler effects and cleaning solutions, the simulation described herein should be refined. Because of the high computational costs associated with it, the resolution of the simulation was limited. Reducing computational cost, reducing the tick length, and relaxing the assumptions required to run the simulation in a reasonable time frame would all increase the value of this research.

In addition to efficiency, the depth of the model can also be enhanced. Modelling the rotation of LEO relative to the earth's surface would provide significant accuracy improvements for the effect of laser brooms on debris populations. Improving the collision model, which is now rudimentary, for derelict spacecraft would help bring the total number of collisions closer to observed values.

Additional work should also be done to better understand the capabilities of ground-based laser debris removal systems. Although research exists on this topic, much of it is decades old. Since the simulation suggests laser brooms are an outstanding performer, additional research on their feasibility and costs with today's technology is warranted.

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Appendix A: Design of Experiments

Cleaner Flag	Launch Rate	Number of Cleaner Satellites	Number of Lasers
1	3456000	2	1
1	864000	1	1
1	864000	0	0
1	4752000	1	0
0	6048000	2	0
0	6048000	1	1
1	6048000	3	1
0	6048000	3	1
1	2160000	0	1
1	864000	2	0
0	4752000	0	0
0	4752000	2	1
1	6048000	3	0
0	2160000	1	1
1	2160000	3	0
0	2160000	2	0
1	6048000	1	1
1	6048000	0	0
1	4752000	2	1
0	3456000	1	0
0	864000	2	0
1	2160000	3	1
0	4752000	0	1
0	2160000	2	1
0	864000	0	1
0	864000	0	0
0	864000	3	1
0	4752000	3	0

Table 1 The design of experiments used for model explorations.