Engineering and Physical Sciences Research Council

Assessing Collision Algorithms for the NewSpace Era

UNIVERSITY OF Southampton

Mr. Samuel Diserens, University of Southampton, *S.D.Diserens@soton.ac.uk*
Professor Hugh G. Lewis, University of Southampton, *H.G.Lewis@soton.ac.uk*
Professor Joerg Fliege, University of Southampton, *J.Fliege@soton.ac.uk*

Introduction

The last two decades have seen a shift towards greater private sector participation in the space industry, as opposed to the traditional operators from governments and the military-industrial complex. This 'NewSpace' era has led to increasing disruption and innovation in the space industry driven by the increased competition of the growing commercial element.

Assumptions are made in many debris models about the characteristics of debris objects and how they can be approximated. In light of the on-going changes in the physical and orbital characteristics is important to re-asses these assumptions to determine if they are appropriate for the NewSpace era and how this affects the validity of the debris models being used to understand the potential future environment.

Collision Modelling

The evolution of the space debris environment can be broken down into several key processes such as collision, fragmentation, atmospheric drag, which have different impacts on the environment. The application of component models of these processes is influenced by the characteristics of debris objects, such as their cross-sectional area when calculating collision probabilities or applying atmospheric drag.

It is expected that the increasing populations of both spacecraft and debris will result in an increased risk of collision events in future. Combined with the fact that the rate of explosions has remained constant since the early seventies, despite an exponential increase in spacecraft population, collision events, instead of explosions, may become the dominant source of new debris objects in future.

Due to the importance of collision events to the future growth of the debris population, this investigation chose to focus on an assessment of algorithms used to predict collisions within computational. Two key algorithms, Cube [1] and Orbit Trace [2], were identified as being used in the majority of current debris models.

Cube

The total number of collisions N_{tot} between a pair of objects i and j is estimated by uniformly sampling the collision rate for a pair of objects, $P_{i,j}$, over the simulation projection period.

$$N_{tot} = \int_{t_{begin}}^{t_{end}} P_{i,j}(t)\, dt = \int_{s=0}^{s=L} [t_{s+1} - t_s]\, P_{i,j}(s) ds$$

Collisions are considered to be possible in the Cube algorithm only if two objects appear within the same small volume of space, normally a cube.

The collision rate for pairs of co-located objects is calculated using the kinetic theory of gas on the scale of the cube:

$$P_{i,j} = S_i S_j V_{rel} \sigma dU$$

Where:

V_{rel} : Relative velocity of the two objects,
dU : Volume of the cube,
S_i / S_j : Spatial densities of objects i and j,
$\sigma = \pi(r_i + r_j)^2$: Collision cross-sectional area.

Orbit Trace

Generates a probability of a collision occurring within a time-step in a pair-wise geometric fashion, looking at the intersection points of the orbit paths. The collision probability for a pair of objects is calculated based on the proportion of the time-step each object spends in the region around the intersection of the orbits using the equation:

$$P_{i,j} = \frac{2 * \sqrt{(r_i + r_j)^2 - d_{min}^2}}{\sin(\alpha)\, v_j\, T_{u,i}\, T_{u,j}}$$

Where:

$d_{\min}$: Minimum separation of the orbits,
v_j : Relative velocity of the impacting object,
α : Angle of intersection
$T_{u,i} / T_{u,j}$: Orbital periods of objects i and j.

Filters are used to reduce the number of pairs considered, by excluding objects in orbits incapable of colliding such as non-proximal objects in synchronised orbits.

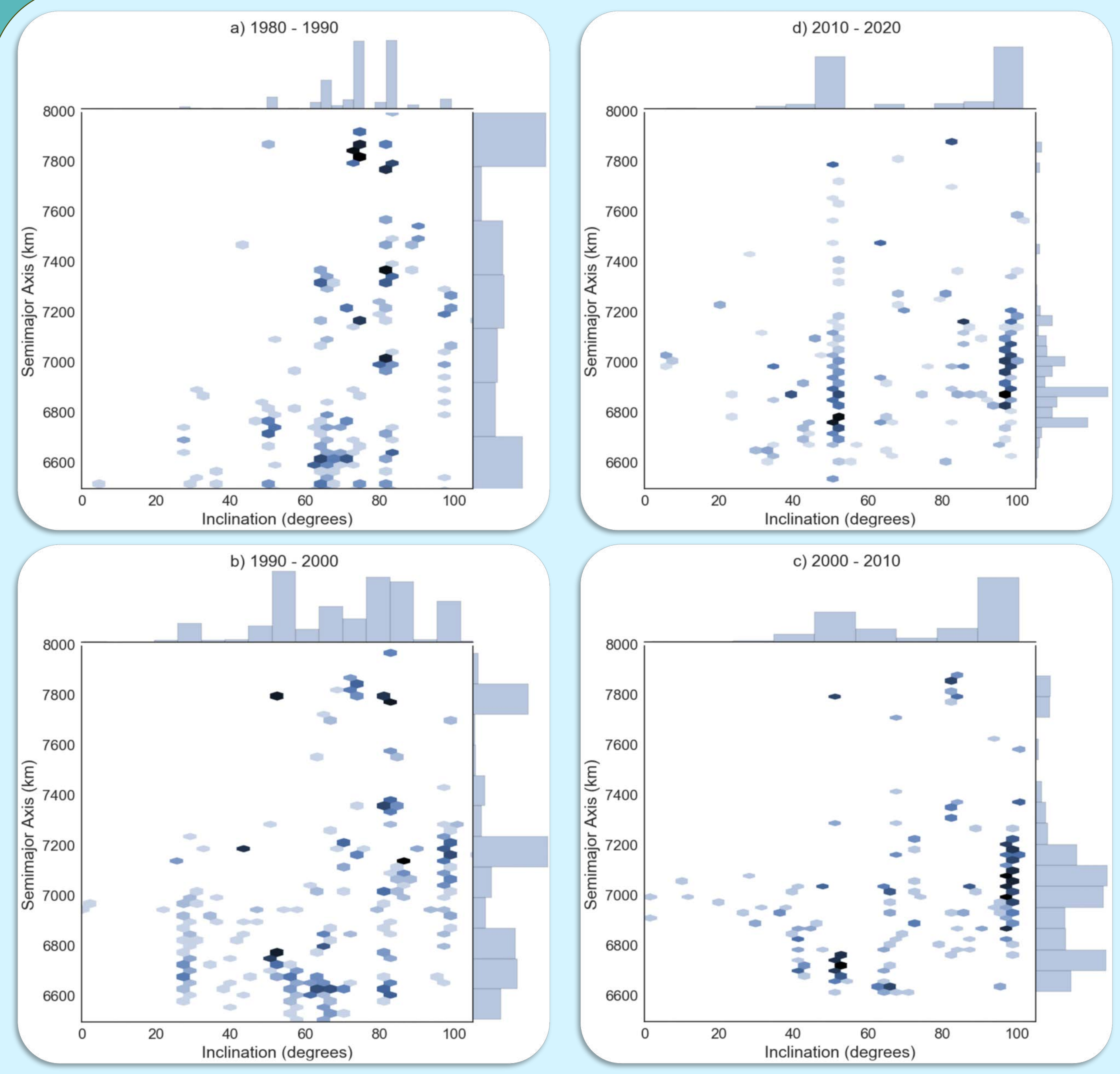


Fig. 3 Plots showing individual histograms and combined 2D hex plots of the distribution of LEO spacecraft across semi-major axis and inclination for (a) 1980-1990; (b) 1990-2000; (c)2000-2010; and (d)2010-2019.

NewSpace Trends

Key orbital and physical characteristics of spacecraft in ESA's DISCOS were analysed for spacecraft launched between 1980 and 2019 for orbits from LEO to GEO. As well as changes in mass and size (towards smaller and lower mass in LEO and larger and more massive in GEO) there have been changes in operational characteristics, including a growing trend towards ridesharing and the launch of multiple spacecraft on the same rocket into similar orbits.

Figures 1 and 2 compare the prevalence of different categories for recent decades. A growth in the proportion of commercial spacecraft can be seen, from 4.6% of launched spacecraft in the 1980s to 55.6% in the most recent decade compared to a reduction in military from 76.5% to only 10.5% of the population. The absolute numbers show that total launches for civil and military spacecraft have remained consistent at around 700 per decade, but were accompanied by a 213% increase in overall launches from the 1980s to the 2010s. Commercial and academic spacecraft account for 208% of this increase, from 34 to 1292 and 5 to 253 launched respectively.

To study the impact of these changes on the spatial distribution of spacecraft the orbital characteristics of the launch population were analysed over the period for the LEO region. The resulting distributions across semi-major axis and inclination are displayed in Fig. 3 (a - d) for each decade. A clear change is observed towards **increased clustering** of spacecraft into **specific regions of altitude and inclination**.

In Fig 3 (d), showing the distribution for the period from 2010 to 2019, there **concentrations** of spacecraft are visible in **two inclination regions**: at **50-55°** (the inclination of the ISS) and **95-100°** (for sun-synchronous orbits). In addition to the inclination banding the figure shows that spacecraft are becoming increasingly concentrated in the lower altitudes, with the majority of spacecraft having **altitudes under 900 km** (a semi-major axis less than 7278 km).

The first two Starlink deployments exemplified the practice of multi-spacecraft launches with each consisting of 60 spacecraft on a single Falcon 9. Large constellations such as Starlink and those planned by OneWeb and Boeing will result in new regions of orbital clustering. SpaceX alone plan on up to 24 Starlink launches in 2020, resulting in a further 1440 spacecraft in similar orbits.

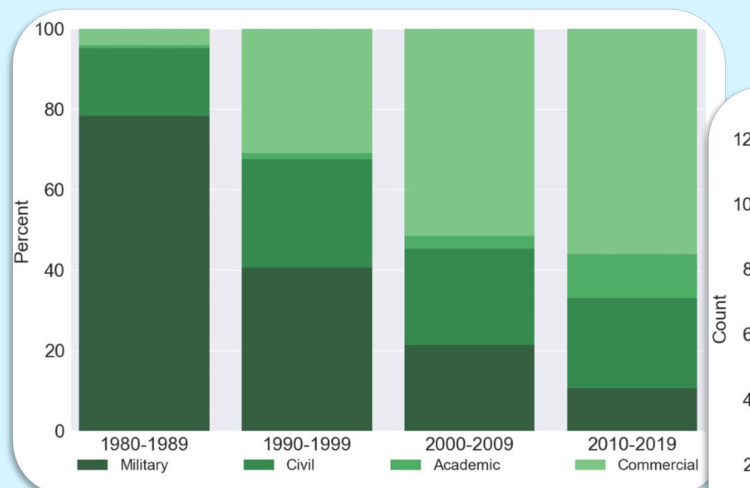
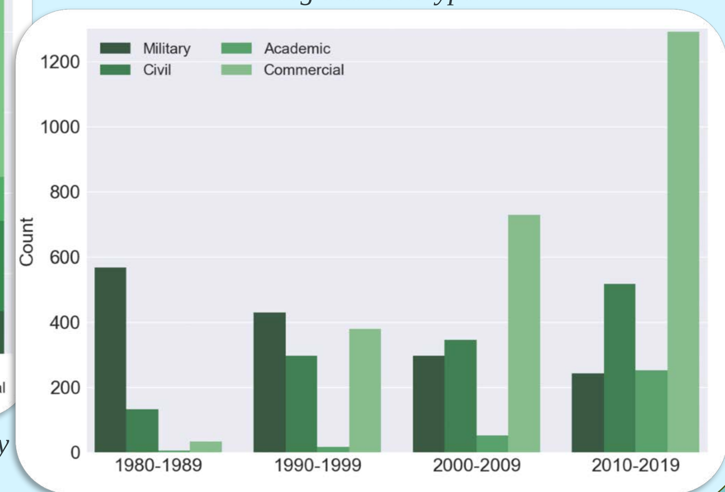


Fig. 1 Percentage of spacecraft launched per decade by organisation type.

Fig. 2 Count of spacecraft launched per decade by organisation type.



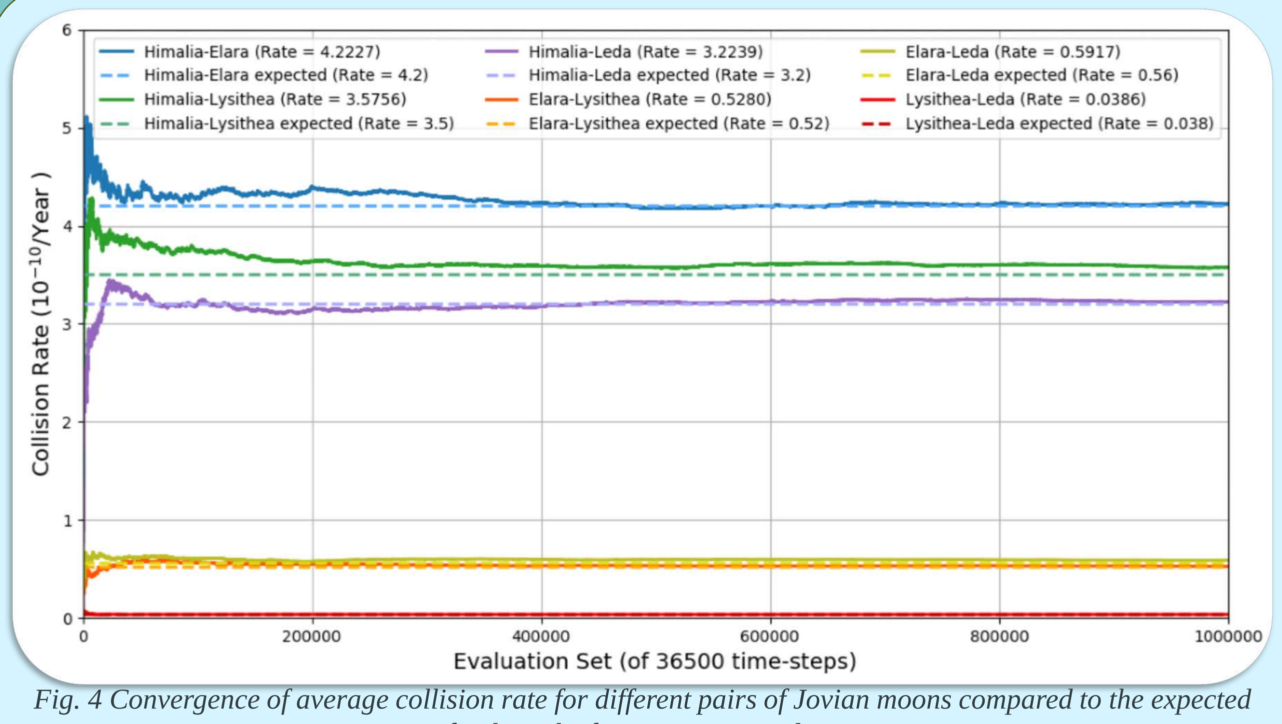


Fig. 4 Convergence of average collision rate for different pairs of Jovian moons compared to the expected final results from previous studies.

Cube Investigation

The Cube algorithm was implemented to better understand the behaviour of the model. Table 1 shows the results using a cube size of 1% of the average semi-major axis of the moons using the collision rates reported by [1] to verify the implementation.

The convergence of these average collision rates was investigated to understand how many samples were required before the rates appeared to have converged. Figure 4 shows how the averaged collision rate converged towards the published results for each pair of moons using 1-day time-steps (average collision rate calculated every 36,500 steps over 1 million different sets for 36.5 billion samples per pair).

Table 1. Comparing the collision rates calculated by different models.

Collision Pair	Kessler (1981)	Kessler (2003)	Liou et al. (2003) - Cube	New - Cube
Himalia-Elara	4.3	4.1	4.2	4.22
Himalia-Lysithea	2.8	3.4	3.5	3.58
Himalia-Leda	3.1	3	3.2	3.22
Elara-Lysithea	0.52	0.51	0.52	0.528
Elara-Leda	0.57	0.57	0.56	0.592
Lysithea-Leda	0.039	0.038	0.038	0.0386

If this rate of convergence holds when modelling the debris environment then the results suggest that a large number of object pairs are required for confidence in the collision rate. It is therefore **unlikely** that an estimate of the **collision rate** between any two objects can be given with any **confidence**.

Figure 5 shows the results of an investigation into the effects of the choice of cube dimension on the performance of the algorithm for the Jovian moons scenario. Values of 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10% and 20% of the average semi-major axis of the system were used with the same random number seed to remove deviation in the position sampling.

The results show a **dependence** on the **cube size** for both the **rate of convergence** and the **converged average collision rate** for the system. **Smaller cubes** require **more steps** to converge and result in a **lower average collision rate**.

Further work is required to understand the nature of the **relationship** between the **cube size** and the **collision rates** to ensure that appropriate configurations are used when simulating the evolutions of the debris environment.

(N.B. In this scenario two additional degrees of freedom exist (right ascension and argument of perigee) compared to simulations of debris in Earth orbit.)

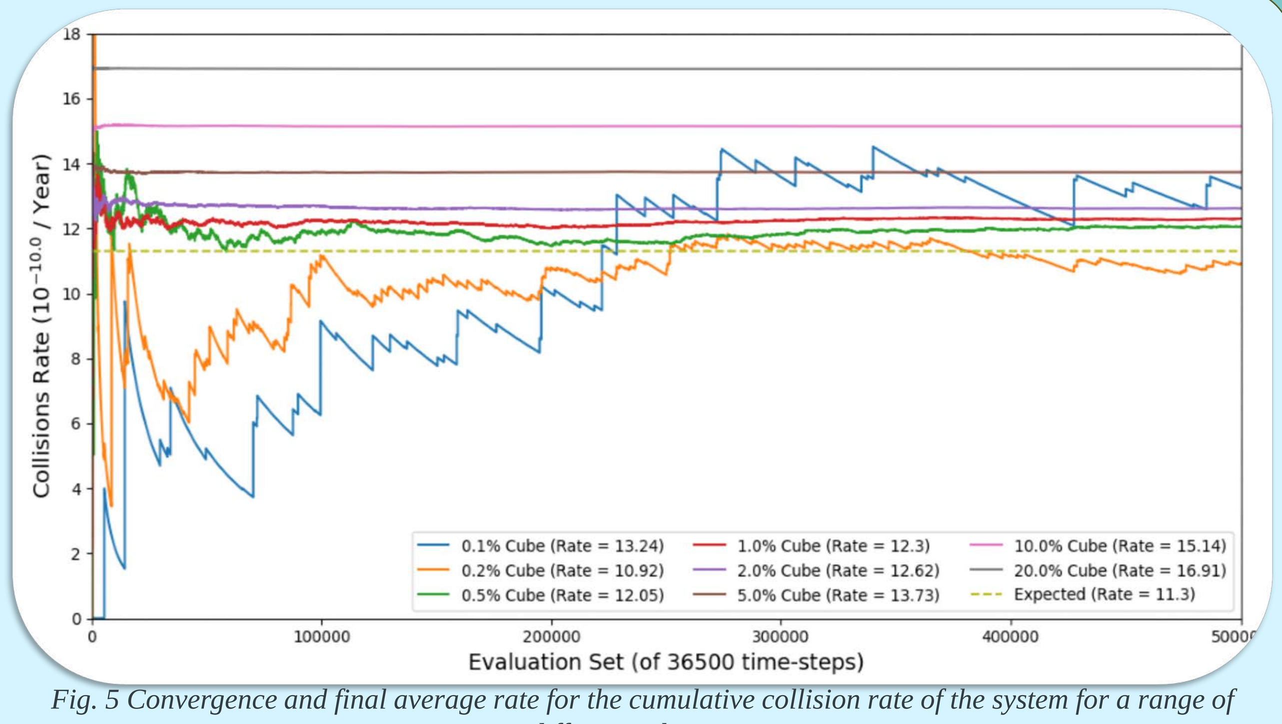


Fig. 5 Convergence and final average rate for the cumulative collision rate of the system for a range of different cube sizes.

Collision Model Comparison

Historical conjunctions recorded in the reports issued by SOCRATES [3] were used to identify primary objects with a high conjunction frequency. Two scenarios, shown in table 2, were used to compare the SCORATES collision probabilities with the results of the Cube and Orbit Trace algorithms in different configurations. For the Cube a range of sizes of cube were utilised, with side lengths from 1 km to 100 km. For Orbit Trace the combined hard-body radius of the objects was replaced with set threshold distances of up to 1 km.

Table 2. Details of test cases used for comparing collision algorithms.

Primary Object	Semi-major axis (km)	Secondary Count	Start Date	Duration (days)	Conjunction Frequency (per day)
42731	6774	46	2017-06-02	519	0.615
49300	6865	83	2018-12-28	70	4.462

Objects were initialised with an assumed a hard body radius of 1 metre using the TLEs closest to the first SOCRATES conjunction. The behaviour of the population was then simulated for a set duration using the SGP4 propagator [4] and a time-step of 0.05 days (~once per orbit). Tables 3 and 4 show a comparison of the results for objects 42731 and 43900 respectively using an average over 10 different simulations for the Cube algorithm. Three different metrics are used for this comparison: the number of conjunctions, the total probability of a collision occurring, and the average collision probability across all pairs.

The methods returned very different results for all three metrics and the differences were not consistent between the two test cases. Both the overall and average collision probability of the **Cube simulations were several orders of magnitude less than the SOCRATES results, while the Orbit Trace results were several orders larger**. Each of the methods is used to quantify the risk of a collision occurring but provides a very different assessment of the risk. These results suggest that there is currently a **poor level of understanding** of the rates at which collisions can be expected to occur in the future.

Looking at NewSpace systems there are **several issues with the use of the Cube algorithm**. In particular, there are issues with the approach of **sampling from the mean anomaly when modelling large constellations**. This randomization of the position is inconsistent with the known relationship of the positions of the constellation spacecraft. This is likely to result in the **over-prediction of collision rates within a constellation**.

Recent trends indicate a shift towards a **higher proportion of spacecraft residing in lower orbits** as well as a trend towards **smaller spacecraft**, such as CubeSats. Due to greater the atmospheric drag force at lower altitudes and the increased difficulty of tracking smaller spacecraft both result in a **larger positional uncertainty**. While this might suggest a larger cube size should be used to capture the greater uncertainty the choice of cube size also impacts the suitability of the application of the kinetic theory of gas within the cube. The collision rate for the Cube is dependent on the collision cross section of the objects and agnostic to the minimum separation. As a result, **increased cube size** would **increase the probability of collisions between large objects** in more separated orbits over collisions between smaller more closely interacting objects.

It is possible that the **Cube algorithm, with its speed benefits, can be used to look at the overall environmental hazard**, even though it is unsuited for studying individual object pairs. **However**, the issues raised by this investigation create **doubt in the results of simulations of the debris environment**. Changes in **which objects** are involved in collisions could substantially alter **how many and at what altitude fragments** are generated which in turn impacts **the life-time of the fragments** produced and **the collision risk** they pose to other objects. This could result in **long term impacts on the evolution** of the debris environment.

Table 3. Results of different collision algorithms for object 42731 with 47 secondary objects over 519 days

Method	Cube Size / Threshold	Detected Conjunctions	Collision Probability	Average Collision Probability
SOCRATES	5 km	320	4.25E-03	4.61E-06
Orbit Trace	2 m (Hard Body Radius)	176	1.00E+00	2.66E-02
Orbit Trace	10 m	906	1.00E+00	4.23E-02
Orbit Trace	100 m	7400	1.00E+00	3.28E-02
Orbit Trace	1 km	56889	1.00E+00	2.37E-02
CUBE*	1 km	3.3	1.18E-05	2.77E-06
CUBE*	2 km	19.3	8.05E-06	4.19E-07
CUBE*	5 km	138.3	6.56E-06	4.73E-08
CUBE*	10 km	603.8	6.39E-06	1.06E-08
CUBE*	20 km	2207.4	6.29E-06	2.85E-09
CUBE*	50 km	10120.5	3.44E-06	3.40E-10
CUBE*	100 km	27723.1	2.03E-06	7.32E-11
* For the cube examples results are averaged over 10 runs				

Table 4. Results of different collision algorithms for object 43900 with 83 secondary objects over 70 days

Method	Cube Size / Threshold	Detected Conjunctions	Collision Probability	Average Collision Probability
SOCRATES	5 km	218	1.20E-03	1.14E-06
Orbit Trace	2 m (Hard Body Radius)	26	1.75E-01	7.05E-03
Orbit Trace	10 m	140	9.75E-01	2.06E-02
Orbit Trace	100 m	1385	1.00E+00	1.51E-01
Orbit Trace	1 km	10885	1.00E+00	7.38E+00
CUBE*	1 km	0.5	5.36E-07	4.34E-07
CUBE*	2 km	3.9	6.19E-07	1.41E-07
CUBE*	5 km	23.4	3.87E-07	1.64E-08
CUBE*	10 km	69.2	5.77E-06	8.85E-08
CUBE*	20 km	154.1	4.12E-06	2.67E-08
CUBE*	50 km	478.6	3.01E-06	6.28E-09
CUBE*	100 km	1146	2.01E-06	1.76E-09
* For the Cube examples results are averaged over 10 runs				

Conclusions

The commercial sector has grown over the last 40 years to and now contributes more than half of new spacecraft launched. As well as changes in the average mass and cross-section of spacecraft this shift has been accompanied by changes in the concepts of spacecraft deployment and operation. One result of these changes is an **increase** in the **clustering of spacecraft** into specific **inclination** bands and **lower altitudes**.

A study of the results of the Cube for the original Jovian moons scenario highlighted that a **substantial variation** existed in the **average collision rate** for an individual object pair after 7 billion samples. For standard simulations of the debris environment consisting of only 14,610 samples in time these results suggest that the **Cube method is not suitable for estimating the collision probability of a specific pair of objects**. Further investigation showed that the **rate of convergence** and the **overall collision probability** of the test case was **dependent** upon the choice of **cube size**. The results showed that for smaller cubes a greater number of samples was required for convergence and indicated a **linear relationship of decreasing collision rate for decreasing cube size**.

A **comparison of different approaches** for the more restricted case of spacecraft in earth orbit showed a **difference** by **orders of magnitude in the total collision probability** when using each of the **SOCRATES, Orbit Trace and Cube methods**. The relation between the SOCRATES results and the results for the different collision thresholds and cube sizes used did **not** appear to be **consistent** between the **two scenarios**. This gave no clear indication of what would be appropriate configurations of the models for consistent results. This leaves **doubt** as to whether **these models can be trusted** as providing an **accurate representation** of the likelihood of **collisions** in the debris environment.

In contrast with the earlier investigation for these scenarios the **overall collision probability** appeared to **increase** with **decreasing cube size** with **larger cube sizes** resulting in significantly **more conjunction** events each with a **lower collision probability**.

Further work is required to investigate the discrepancies between the different algorithms, including to determine if the high overall collision probability of the Orbit Trace configurations are valid or being caused by a few anomalous events. As well as a more detailed investigation into the Orbit Trace algorithm future work is planned to determine if the models introduce any **bias towards collisions at different altitudes** by comparing how the agreement for these different methods varies for debris populations in different orbital regions.

References

[1] Liou, J.-C., et al. A New Approach to Evaluate Collision Probabilities among Asteroids, Comets. Lunar and Planetary Science, XXXIV: 2-3, 2003.
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