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Safety considerations for large constellations of satellites

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ABSTRACT

The deployment of constellations of satellites within low Earth orbit (LEO) has implications for space operations and for the broader space environment. A large active satellite population will experience high numbers of conjunctions with other resident space objects (RSOs). Even if only a small proportion are high-probability events, the substantial number of conjunctions will still lead to many potentially high-risk encounters with other RSOs and a correspondingly high burden for their operators to mitigate them via maneuvers. This burden is exacerbated if the operator adopts an approach whereby risk mitigation maneuvers are conducted at collision probability levels below the widely accepted 1E-4 (1-in-10,000). Despite these significant efforts the remaining aggregate risk may still be relatively high because of the large number of conjunctions experienced by some constellations, leading to ongoing concern over the safety of these space systems. Through an analysis of conjunction assessment data, simulations using the DAMAGE computational model, and a new mapping approach, the risks from conjunctions between large constellations and other RSOs have been investigated. The results show that some existing constellations currently face more than a 10 % annual collision probability even after accounting for their robust risk mitigation approaches, with implications for the safety and long-term sustainability of large constellations and the broader LEO environment. Overall, the work emphasizes the need for new research and guidance on this aspect of space operations.

1. Introduction

The resident orbital object (RSO) population in low Earth orbit (LEO) grew by nearly 50 % from approximately 19,000 in November 2018 to 28,000 in November 2023, driven primarily by the deployment of the first of many planned large constellations of satellites by commercial organizations. Constellations of satellites support low latency communications and Earth observation with rapid revisit, but they require large numbers of satellites at LEO altitudes within an environment already classed as the highest risk orbit [1]. Licensing requirements typically demand expedited deployment schedules for these space systems. The combination of many satellites being launched over a relatively short timescale and their near-ubiquitous use of continuous low-thrust propulsion to traverse the lower LEO region after insertion has had substantial consequences already for space operations [2].

Research using computational models to understand potential impacts on space sustainability has shown that successful post-mission disposal provides an important debris mitigation measure for large constellations [3]. Operators have generally held themselves to stricter requirements than those described in the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines or Federal Communications Commission (FCC) rules [Anon., 4]. Indeed, several operators have targeted low altitudes for the deployment of large constellations because satellites in these orbits will decay naturally within the required post-mission lifetime without heightening sustainability concerns. At these low altitudes the atmospheric density is such that spacecraft can decay within a few years, thereby meeting the expectation that they will be removed from the LEO region within 25 years (IADC) or 5 years (FCC) even if they were to fail.

In addition to sustainability concerns, the deployment of large numbers of satellites within this critical orbital region has implications for managing the safety of space operations. Collisions between RSOs would pose a risk to operational spacecraft, as well as to the wider space environment through their potential to generate large quantities of debris and further collisions. Hence, efforts to mitigate this risk are vital components of the management of the orbital environment. For this reason, the United States Space Force 19th Space Defense Squadron (19 SDS) performs conjunction assessment (CA) for global commercial, civil, military, and academic operators. Nearly 180 million Conjunction Data Messages (CDMs) covering approximately 3 million unique

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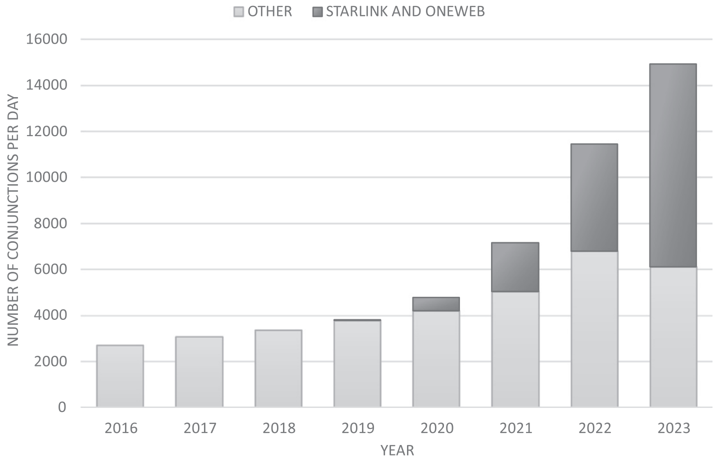

Fig. 1. Change in the conjunction rates predicted by SOCRATES from 1 January 2016 to 30 March 2023.

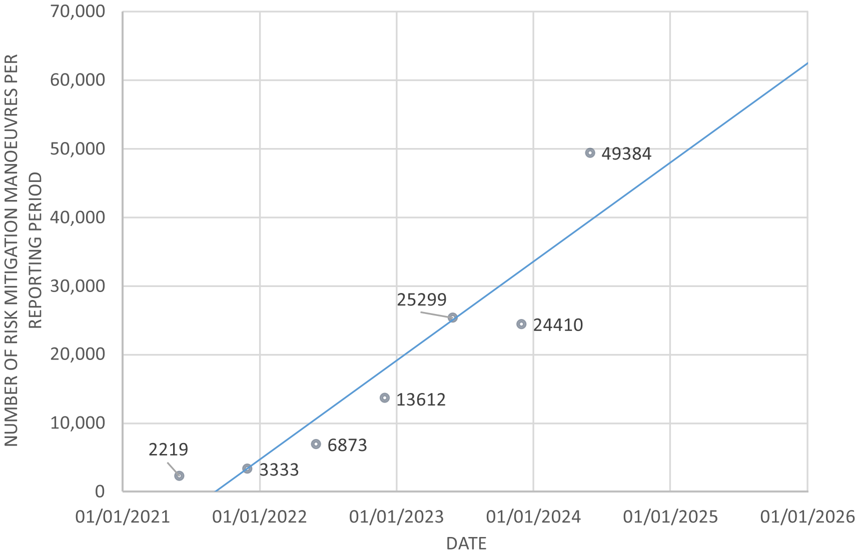

Fig. 2. Number of conjunction risk mitigation maneuvers performed by satellites from the Starlink constellation in six-monthly periods covering December 2020 through May 2024 as reported to the FCC. The linear model has a gradient of approximately 40 maneuvers per day.

conjunction events were generated for the period 1 January 2016 to 31 December 2021 [1]. 19 SDS currently generates approximately 600,000 Conjunction Data Messages (CDMs) per day, an increase of 200 % over the daily rate from just three years ago [2,5]. Satellites from the Starlink and OneWeb constellations appear as primary or secondary objects in nearly two-thirds of these daily messages [2]. Conjunction predictions from Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES; https://celestrak.org/SOCRATES/) for the period 1 January 2016 to 31 March 2023 also show the significant influence of these two large constellations over the last few years (Fig. 1).

Even if only a small proportion are high-probability events, the substantial number of conjunctions will still lead to many potentially high-risk encounters with other RSOs and a correspondingly high burden for their operators to mitigate them. A widely accepted value of the collision probability threshold at which an operator chooses to mitigate a conjunction is 1E-4 (1-in-10,000) [6]. This threshold is commonly understood to offer a sensible balance between safety and impacts on the mission. Nevertheless, some large constellation operators have chosen to adopt a lower probability threshold (e.g., 1E-5 or 1-in-100,000) meaning that mitigation actions, usually in the form of maneuvers to change the satellite's trajectory, are conducted more frequently (e.g., Fig. 2). A high maneuver rate within any constellation will also create a series of new of conjunction reports [2].

Equally, there will be a large proportion of low-probability conjunction events with other RSOs where the collision probability threshold for a maneuver is not reached. Traditionally, the risk associated with these low-probability events is accepted by the operator because the maneuvers needed to mitigate them would quickly deplete spacecraft resources and impact the mission. However, for large constellations the risk accumulated from the very large number of low-probability conjunctions can be significant.

When a conjunction risk mitigation maneuver is performed, the conjunction geometry as well as the timing of the closest approach change accordingly, thereby reducing the collision probability. NASA recommends that risk mitigation maneuvers deliver a reduction of the collision probability by 1.5 orders of magnitude [6]. Although the FCC recognize that the risk is not removed entirely by these maneuvers, a common approach adopted by the Commission and some operators is to assume the collision probability "*to be zero or near zero for spacecraft that have a maneuver capability and a process for identifying the need for and executing collision avoidance maneuvers*" [7]. The Commission argues that collision probabilities from conjunction warnings may not provide a reasonable measure of the residual risk and may instead be an ar-

Table 1
Analyzed satellites and constellations. For constellations, the conjunction screening covers all satellites in the constellation in orbit at the time. The mean Pc is the average collision probability calculated using the maximum collision probability method for conjunctions from 1 January 2016 (or from first deployment) to 31 March 2023.

Name / Constellation / Maneuverable	Number of conjunctions identified in SOCRATES data Jan 2016 to Mar 2023	Number of conjunctions identified in SOCRATES data Jan 2022 to Dec 2022	Mean Pc
Flock / ✓ / ✗	783,264	214,884	7.30E-6
Iridium / ✓ / ✓	1262,722	261,245	1.60E-5
OneWeb / ✓ / ✓	457,527	193,376	2.88E-6
Starlink / ✓ / ✓	3601,677	1603,137	3.10E-6
Sentinel 1A / ✗ / ✓	9829	2383	1.30E-6
Envisat / ✗ / ✗	8178	1271	7.41E-5
Flock 4S-20 / ✗ / ✗	2001	1010	2.92E-6
Iridium 135 / ✗ / ✓	6870	1402	7.22E-6
OneWeb 0426 / ✗ / ✓	1462	1304	9.65E-7
Starlink 3528 / ✗ / ✓	1016	610	1.26E-6

tifact of risk modelling methods rather than actual risks. Nonetheless, when combined with the level of residual risk from the many low-probability conjunctions not reaching the maneuver threshold, this assumption has the potential to ignore a sizeable risk to the safety of large constellations. Given the uncertainty and the importance of the residual risk for these cases, a new analysis of conjunction assessment data has been undertaken and is reported below. Simulations using the DAMAGE computational model and a new mapping approach have also been used to investigate the potential significance of residual risks from conjunctions between large constellations and other RSOs.

2. Data and simulation approach

SOCRATES conjunction predictions from 1 January 2016 to 31 March 2023 were the primary data used for this analysis. SOCRATES predictions for this period were generated three times per day for all satellite payloads in orbit against all RSOs using the full catalog of all unclassified elements and for conjunctions within 5 km at Time of Closest Approach (TCA). SOCRATES conjunction predictions are made using the Ansys Systems Tool Kit Conjunction Analysis Tools (STK/CAT), which reports the maximum collision probability (Pc) for the conjunction [8]. Screening for conjunction events occurs seven days prior to the estimated TCA and the regular re-screening produces updated predictions for the same conjunction prior to TCA. The best representation of each unique conjunction event in the SOCRATES data was identified through a filtering process and from the latest screening prior to the TCA as described in [1]. From the unique conjunction events found, those covering some key constellations and a selection of payloads (as detailed in Table 1) were analyzed.

The aim of this work was to investigate and understand the significance of the residual collision probability for large constellations. The approach made use of a conjunction risk map that provides information about the annual collision probability. The large constellations and satellites in Table 1 were placed on this map enabling easy comparisons and a simple, clear representation of the risk that each system or satellite is exposed to through interactions with other objects in the space environment.

For events that occur with a known constant mean rate, λ, and independently of the time since the last event, the probability that x events will occur in a fixed interval of time is [9],

$$f(x) = \frac{\lambda^x e^{-\lambda}}{x!} \tag{1}$$

where e is Euler's number and ! is the factorial operator. A mean yearly collision rate, λ_c, can be defined as,

$$\lambda_c = N\overline{P_c} \tag{2}$$

where N is the number of conjunction events occurring in one year with a mean collision probability $\overline{P_c}$. From Eq. (1) the probability that no collisions occur in the year is found by setting $x = 0$,

$$f(x) = \frac{\lambda_c^x e^{-\lambda_c}}{x!} = e^{-\lambda_c}, \tag{3}$$

and the probability that there will be at least one collision in the year is then,

$$P = 1 - e^{-\lambda_c} \tag{4}$$

Each satellite of interest is placed within the conjunction risk map at coordinates corresponding to $(N, \overline{P_c})$. Its location can then be understood in relation to lines of constant annual probability, P.

2.1. Data investigation and corrections

The collision probabilities associated with conjunction events can vary across many orders of magnitude, very rarely reaching levels greater than 1E-3 and much more frequently falling below 1E-6. The resulting Pc distribution will have a distinctive shape if enough conjunction events are included (e.g., Fig. 3). This shape is determined predominantly by factors intrinsic to the use of the maximum collision probability method with the full catalog of all unclassified general perturbations element sets (Two Line Elements; TLEs). For cases where relatively few conjunction events are recorded (e.g., covering individual payloads over relatively short time periods) the full distribution will only be partially complete. This *under-sampling* will result in an error for the predicted mean of the Pc distribution. It is reasonable to expect the Pc distribution for an individual satellite in a large constellation to closely resemble the Pc distribution generated from all satellites in the constellation.

It is widely known that TLEs contain significant errors in the trajectories of RSOs. Their use in SOCRATES will subsequently lead to errors in predictions of conjunction events. However, as SOCRATES remains the only public domain source of conjunction data covering all unclassified orbital payloads, and no suitable alternative source with the same comprehensive coverage was available in the study timeframe, its use was necessary for the analysis. Consequently, and as far as it was possible to do so, it was prudent to undertake a comparison with more accurate CDMs. The latter also incorporate uncertainties due to assumptions related to the sizes (hard body radii) of the RSOs involved in the conjunctions, generally leading to a conservative bias in Pc predictions. The bias was not addressed in this study and remains a limiting factor in the accuracy of the method overall.

Reference [1] reports on a process that grouped approximately 30 million CDMs into 2906,984 unique conjunction events with primary objects being limited to payloads and covering the period 2016 through 2021. This count was considered as the "true" number of conjunctions over this period. Analysis of the SOCRATES conjunction predictions using the process from [1] revealed 8962,469

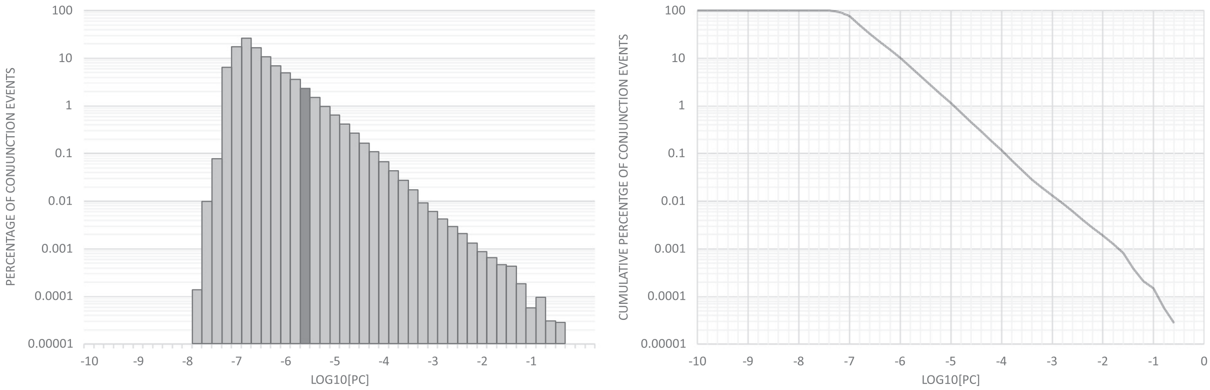

Fig. 3. Proportion (left) and cumulative proportion (right) of conjunction events with specified collision probabilities for SOCRATES-based predictions covering Starlink satellites from first deployment in May 2019 to March 2023. The location of the mean (Pc = 3.10E-6) is shown using the dark grey bar.

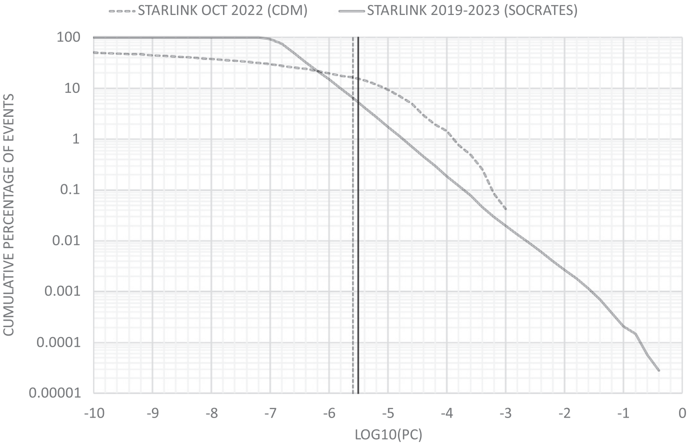

Fig. 4. Distributions of the cumulative proportion of conjunction events involving satellites from the Starlink constellation based on CDM and SOCRATES data. The solid vertical line indicates the mean Pc computed from the SOCRATES data and the dashed vertical line indicates the same for the CDM data.

unique conjunction events for the same period, a factor of 3.08 higher.

4716 CDMs from Space-Track covering October 2022 for several satellites operating near 550 km were analyzed. Nearly all the CDMs for these satellites were for conjunctions involving Starlink satellites. A comparison of the Pc distributions for the SOCRATES-based conjunctions (from 2019 to 2023) and the CDM-based conjunctions are shown in Fig. 4. The mean Pc calculated from the CDMs was 2.54E-6, which represents a difference of approximately 5.5E-7 from the mean Pc derived from the SOCRATES-based conjunctions. At first glance the correspondence between the mean Pc values appears to be good, but as well as being limited to CDMs only covering these specific satellites, the comparison is not wholly like-for-like: the SOCRATES data used in the study were based on conjunction predictions close to the TCA whereas the CDMs included the typical evolution of collision probability, where the risk first rises, passes through a peak, then drops as the time to the TCA is reduced with successive screenings [10].

Some payloads can perform conjunction risk mitigation maneuvers. As already observed, risk mitigation maneuvers modify the conjunction geometry and the TCA to reduce the collision probability for the event, generally by 1.5 orders of magnitude [8,11]. They are only performed in response to high-risk events, which account for a very small proportion of all the conjunction events (e.g., about 1 % of SOCRATES-based conjunction events involving Starlink have Pc > 1E-5) but still represent a significant fraction of the overall risk because of their high Pc values. Hence, risk mitigation maneuvers will modify the Pc distribution and the mean Pc.

For the purposes of this study, it was assumed that the mean Pc values from the SOCRATES-based conjunction data were good representatives of the mean Pc values that could be obtained from CDMs and before accounting for any maneuvering ability. For payloads with maneuvering ability, the mean Pc was assumed conservatively to be 0.5 orders of magnitude below the value obtained from the SOCRATES data. Additionally, a correction factor of 1/3 was applied to SOCRATES-based estimates of the conjunction rates to align them with the expected conjunction rate from CDMs. No corrections were applied to the mean Pc values for the individual satellites in Table 1 to account for under-sampling effects.

2.2. DAMAGE simulation

In addition to the analysis of SOCRATES conjunction data, the DAMAGE computational model [12] was used to simulate a large constellation comprising 36,000 satellites operating at altitudes between 320 km and 720 km. Outputs from the simulation included conjunction rates and mean Pc estimates.

DAMAGE is a high-fidelity three-dimensional physical model capable of simulating the evolution of future debris populations. The process used in DAMAGE to build and subsequently replenish constellations is based on a launch schedule comprising the number of launches per year, the number of satellites on each launcher, and the duration over which the build and replenishment are to take place. If an electric propulsion option is selected, a low altitude deployment from the launcher can be specified and the DAMAGE orbital propagator will compute the ascent trajectories for the constellation satellites, incorporating a user-specified thrust level. Satellites launched via the replenishment schedule replace the corresponding satellites in the constellation and the older satellites are retired even if they have not reached the end of their service lifetime, adopting the user-specified post-mission disposal behavior. Once in service, the satellites maintain their within-plane spacing and inter-plane spacing subject only to Earth zonal gravity perturbations. The Concepts of Operations (ConOps) for all satellites in a constellation are constructed from a set of waypoints, which identify orbital elements and times from orbit insertion through to passivation [3].

Following the approach adopted for IADC simulation studies, e.g., in [12], the basic simulation parameters used for this study were:

- A 1 October 2019 epoch with an initial population corresponding to all objects ≥ 10 cm residing within or crossing the LEO

Table 2
Mean number of conjunctions, mean Pc, and respective standard deviations estimated for the four MC runs of scenarios 1–3.

Scenario	ACPL	Mean number of conjunctions per year and standard deviation	Mean Pc and standard deviation
1	1E-4	1.18E7 (16.3 %)	5.49E-7 (2.3 %)
2	1E-5	1.1E7 (8.9 %)	3.40E-7 (2.8 %)
3	1E-6	1.0E7 (8.3 %)	1.71E-7 (1.8 %)

protected region and a projection period ending on 1 January 2024. Existing large constellations (i.e., Starlink and OneWeb) were not included.

- Launch traffic, excluding the large constellation, was assumed to be represented by the repetition of launches from 1 January 2010 to 31 December 2017.
- New spacecraft and rocket stages in the non-constellation traffic were assumed to achieve a 90 % success rate with respect to post-mission disposal, targeting re-entry within 25 years.
- Vehicle passivation was assumed to be 100 % successful such that no explosions occurred within the projection period.

The large constellation added to this reference case comprised 36,000 satellites divided equally amongst 20 distinct orbital shells, each separated by 20 km and with the first shell at an altitude of 320 km. Satellites within each orbital shell were arranged in a Walker-Star geometry, with satellites in 30 orbital planes inclined at 96°. Satellites were assumed to be 600 kg and present a collision and drag cross-section of 4 m^2 for atmospheric drag reduction and collision risk mitigation while operational and 30 m^2 once passivated. Constellation deployment commenced on 1 January 2020 with the complete deployment of all satellites by the end of 2022 and constellation replenishment starting 1 January 2023. The relatively short satellite design life of 3 years and the frequent replenishment are not representative of existing systems but were selected to enable a simulation incorporating the complete deployment of the constellation and one replenishment cycle within the short projection period. The short projection period was necessary because of the high computational load associated with the M-space approach used to identify conjunctions between the constellation satellites and the debris population [13]. All satellites were injected into an initial circular orbit at an altitude of 300 km before ascending to their respective mission altitudes after a 5-day checkout period using electric propulsion. Rocket stages used to deploy the satellites were assumed to de-orbit immediately. Satellite disposal occurred in two stages: an initial descent to a circular staging altitude 5 km below the shell altitude followed by continuous thrust to achieve an eccentric orbit with the perigee at an altitude of 250 km and the apogee at the staging altitude. The disposal success rate was assumed to be 100 % however some satellites could be subject to failures occurring at any point within their operational life. Failures occurring at relatively low altitudes can still result in a successful re-entry.

Intra-constellation conjunctions were ignored but all other conjunctions were identified using a method based on the M-space approach to account for all events between time-steps [13]. Collision probability was calculated using the maximum probability method. When the collision probability was determined to be above a user-specified threshold, the Accepted Collision Probability Level (ACPL), constellation and other operational satellites were assumed to perform a risk mitigation maneuver to reduce the collision probability by 1.5 orders of magnitude before determining whether a collision would occur.

Four scenarios were simulated with constellation ACPL [1E-4, 1E-5, 1E-6, 1E-4] and satellite failure rate [0 %, 0 %, 0 %, <1 %] varied within each. Due to the computational load associated with the M-space approach, only four Monte Carlo (MC) runs were conducted for scenarios 1–3 and one MC run for scenario 4. The MC run for scenario 4 terminated early before constellation replenishment commenced. Variations within each MC run included the right ascension of the ascending node of the first constellation satellite, the orbits of the launch traffic, the geomagnetic activity, and the size and orbits of fragments produced by any collisions. Due to such variations, statistical work in [14] supports the use of at least 60 MC runs for the delivery of robust estimates of the mean or median number of objects or number of collisions at the end of a 200-year projection period. Arguably, the substantially shorter projection period used for the DAMAGE simulation reported here should have required fewer MC runs for robust estimates of the mean number of conjunctions and the mean Pc. Nonetheless, the use of only four MC runs represents a limitation in the approach that should be addressed in future work.

3. Results and analysis

A summary of the key results for scenarios 1–3 – the mean number of conjunctions per year and the mean PC – is shown in Table 2. The standard deviations are shown as percentages of the mean values.

Results for the second DAMAGE simulation scenario (ACPL = 1E-5, 0 % failure rate) showing the evolution of the number and altitude of conjunction events in the LEO region are presented in Fig. 5. Before the deployment of the constellation the annual conjunction and maneuver rates (for operational satellites) were approximately 3.9 million and 100, respectively. For the period 1 January 2020 through 31 December 2023 (i.e., following the start of the constellation deployment), the average annual conjunction and maneuver rates were approximately 11 million and 360,000. These values represent an increase in the annual conjunction rate by a factor of nearly 3 and an increase in the annual maneuver rate by a factor of about 3700. The substantial increase in the latter is due primarily to the significant increase in the number of operational satellites in the constellation with the ability to maneuver and a corresponding increase in the number of conjunctions. On average, each satellite in the constellation was involved in approximately 500 conjunctions and maneuvered about 17 times annually. When the collision probability threshold for maneuvers decreased to 1E-6 (scenario 3), each satellite in the constellation maneuvered approximately 36 times per year on average, doubling the total maneuver rate for the constellation. A key effect of the high maneuver rate, not represented in the simulation, is the degradation in Space Situational Awareness (SSA) accuracy. Reference [15] asserts that "*Maneuvers and associated maneuver uncertainties are a leading cause of degradations in safety and SSA accuracy, timeliness and often render flight safety products insufficient to meet spacecraft operator needs.*" Although technology and software advances offer potential solutions, the high maneuver rates observed in the simulation and reality (see Fig. 2) remain as immediate concerns.

Despite the high maneuver rate and zero failure rate in the simulated constellation, catastrophic collisions involving operational constellation satellites did occur at a rate of about 1 per year in scenarios 1 and 2 (ACPL = 1E-4 and 1E-5) and at a rate of about 0.2 per year in scenario 3 (ACPL = 1E-6). In most cases, the col-

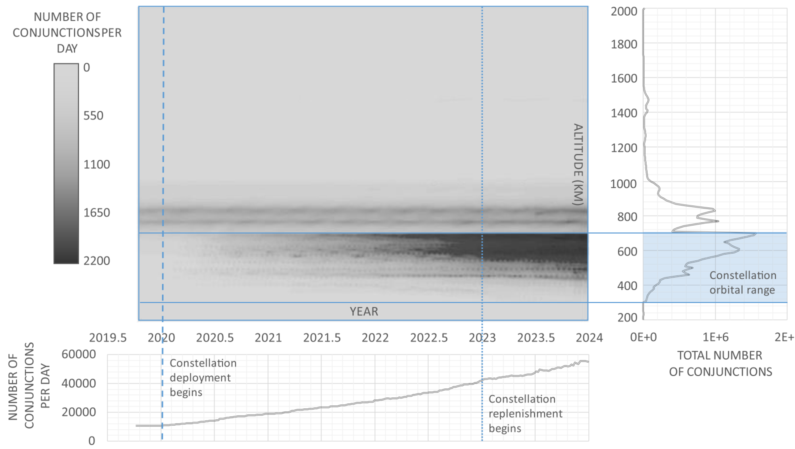

Fig. 5. Evolution of the number and altitude of conjunctions in LEO for the first simulation scenario (ACPL = 1E-5, 0 % failure rate).

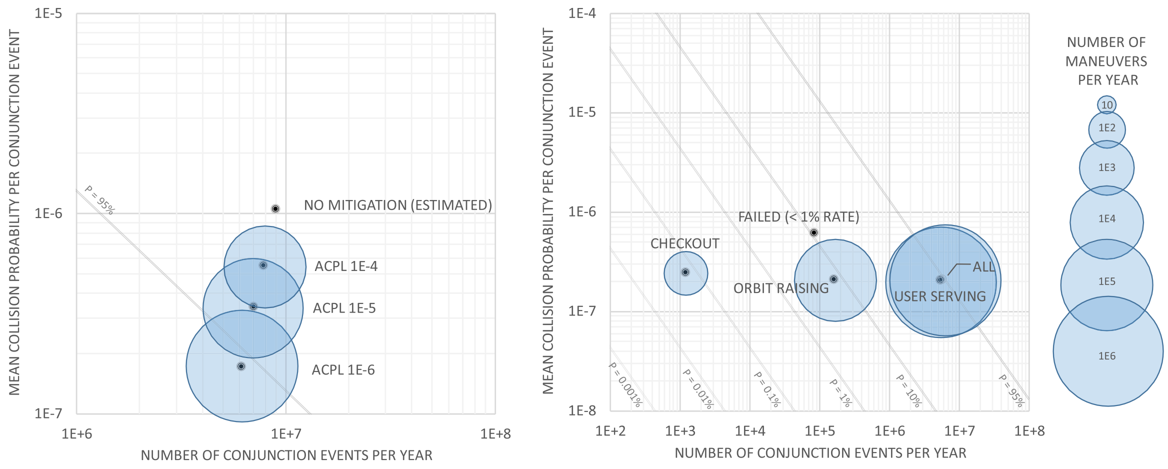

Fig. 6. Conjunction risk maps showing the simulated constellation for different collision probability thresholds (left) and for different mission phases assuming a collision probability threshold of 1E-6 (right). The corresponding annual maneuver rate and lines of constant annual collision probability are also shown. Placement of elements in this map incorporates the effect of risk mitigation maneuvers.

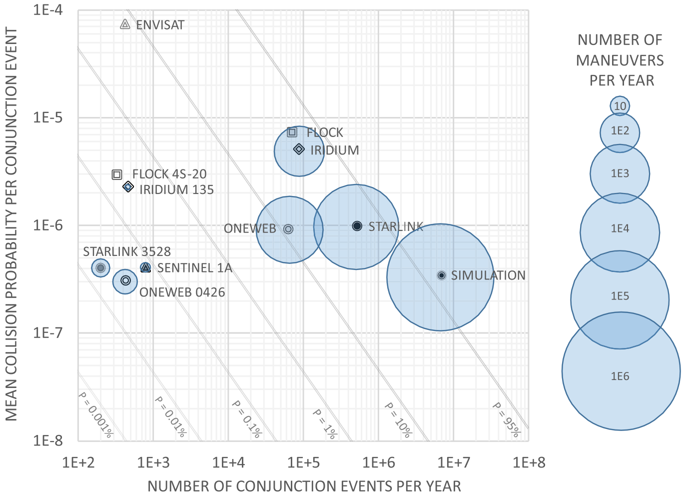

Fig. 7. Conjunction risk map showing constellations and satellites from Table 1 in relation to lines of constant annual collision probability and estimates of the annual maneuver rate for the year 2022.

lision probability was below the maneuver threshold (e.g., one instance Pc = 7.87E-8 or 1-in-13 million) and a maneuver was not performed. These results show good correspondence with the conjunction risk map shown in the left panel of Fig. 6, which is based only on the annual conjunction rate and mean Pc. The map incorporates the effect of conjunction risk mitigation maneuvers.

The right panel of Fig. 6 shows the conjunction risk map for scenario 4 separated into the different mission phases of the constellation satellites, including satellites that failed in the projection period (but not including active disposal or planned end-of-mission phases due to the early termination of the MC run). Although a low failure rate was used in the simulation, the results suggest that the user-serving phase presents the greatest risk, by nearly an order of magnitude, despite an ability to maneuver to mitigate the collision probability. Arguably, if the failure rate were to increase this would also increase the associated conjunction rate and move this point in the map to the right, corresponding to an increased risk. However, the conjunction rate associated with failed satellites would need to rise by one or two orders of magnitude to achieve the same risk level as the user-serving satellites. Even with a full simulation of scenario 4, which would have included some additional – but still relatively few – satellite failures, the user-serving phase would have remained the primary source of conjunction risk in the simulation. This implies that a focus on satellite failure rates, when evaluating collision risks for large constellations, may be misdirected and a better understanding of the residual risk for maneuverable satellites is needed.

Finally, the conjunction risk map for the constellations and satellites in Table 1 is shown in Fig. 7. The map includes corrections to the data as specified in section 2.1 and accounts for the effects of risk mitigation maneuvers. The map suggests that some existing constellations currently face $a > 10\ \%$ annual collision probability despite their operators adopting robust approaches for managing system safety.

4. Conclusions

Using a combination of conjunction data analysis, simulation, and a novel conjunction risk mapping approach, the safety of large constellations has been investigated, with a particular focus on residual risks. The results suggest that some existing constellations currently face $a > 10\ \%$ annual collision probability even after accounting for their robust risk mitigation approaches, which have already led to 10 s of thousands of maneuvers. Constellation collision risk is predominantly associated with satellites in a user-serving phase rather than with failed satellites. This risk arises from the residual collision probability remaining after any maneuvers are performed. The simulation results suggest that even with an enhanced approach to safety (e.g., reducing the collision probability threshold for a maneuver) it is likely that some constellations will continue to experience high annual collision probabilities even while increasing their maneuver burden and potentially degrading SSA accuracy. Additionally, results for the simulated constellation provide valuable insight into the potential risk outcomes for planned constellations comprising 10 s of thousands of satellites, suggesting an even more challenging landscape. If the residual risks are real and are not artefacts of risk modelling methods, then new approaches to manage constellation safety are needed urgently. Given the uncertainty and implications of the answer, further research effort on this topic is vital.

Declaration of competing interest

Hugh Lewis is a Professor of Astronautics at the University of Southampton, UK. He is a also a member of the UK Space Agency delegation to the Inter-Agency Space Debris Coordination Committee. Georgia Skelton is a student at the University of Southampton. No external source of funding was used to support this work. There are no other interests to declare.

CRediT authorship contribution statement

Hugh G. Lewis: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Georgia Skelton:** Conceptualization, Formal analysis, Investigation, Writing – review & editing.

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