IAC-14-A6.4.1

AN ASSESSMENT OF CUBESAT COLLISION RISK

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In their 2011 paper, Oltrogge and Leveque encouraged the CubeSat community to take leadership roles in space debris assessment, ensuring that debris guidelines and standards are met and by implementing effective debris mitigation strategies. However, common misconceptions about the role of CubeSats in the evolution of the space debris environment remain today. For example, up to two-thirds of all CubeSats launched to-date are predicted to remain on-orbit for more than 25 years. In addition, CubeSats have contributed more than 360,000 unique events since November 2005 to the record of satellite conjunctions produced by Celestrak's Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES). To provide some clarity on this issue, a database of CubeSats containing their launch history and relevant physical parameters has been developed for use within the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE), which has been employed to assess the future collision risk from CubeSats. The probability and likely characteristics of conjunctions involving CubeSats have been estimated for a 30-year projection from 1 January 2013 of the low Earth orbit (LEO) population of objects ≥ 10 cm. Three CubeSat launch traffic scenarios were modelled using Gompertz logistic functions with maximum launch rates of 205, 560 and 700 CubeSats per year. These CubeSat launches were added to regular launch traffic, which was based on historical launches from the period 2005 to 2012. Further, calibration of DAMAGE conjunction predictions for the historical period 2005 to 2013 with those recorded by SOCRATES enabled the true number of conjunctions involving CubeSats to be estimated for the future projections. Results show that, even for a relatively low launch rate, CubeSats are anticipated to be involved in 16.5 to 165 million conjunctions in the next 30 years and, potentially, catastrophic collisions as early as 2014. Whilst CubeSats are relatively small, they are nevertheless involved in high-speed conjunctions with large, resident LEO spacecraft and debris in SOCRATES and DAMAGE predictions. To reduce the risks, some effort is needed to engage with the growing small satellite community, and to encourage them to contribute to and, ultimately, lead on sustainable practices and debris mitigation activities.

I. INTRODUCTION

CubeSats are small satellites that have a volume of 10×10×10 cm and a mass up to 1.33 kg (or multiples of this) and are typically used for space research. The CubeSat project began in 1999 as a collaboration between California Polytechnic State University at San Luis Obispo and Stanford University, with the aim of providing a standard for the design of picosatellites that would lead to a reduction in the development time and cost to access space. [1]

Typical applications for CubeSats include education, remote sensing, space and Earth science, in-orbit inspection and technology development (Fig. I). Since the introduction of the CubeSat approach, many universities, schools and private companies have taken advantage of the opportunities they provide for placing small payloads into Earth orbit. Between 2003 and 2013, more than 160 CubeSats were launched successfully into low Earth orbit (LEO), and in June 2014, a Russian Dnepr rocket launched a record-breaking thirty-seven satellites into LEO. [2]

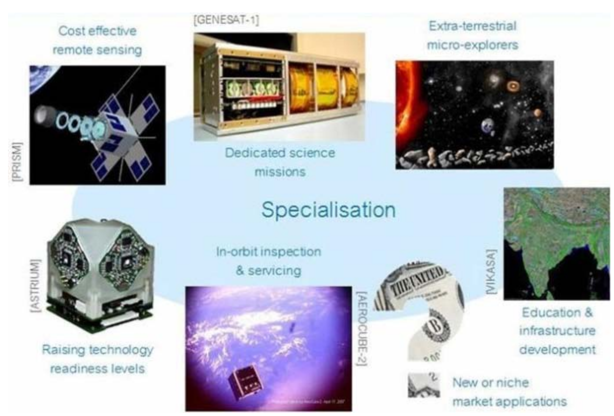

Fig. I: CubeSat applications (image courtesy of Clyde Space Ltd.)

Whilst CubeSats provide increasing opportunities for small payloads to access space, there are some who consider the rapid increase in the number of organisations developing and flying CubeSats as a concern:

"*The proliferation of the aforementioned Cubesats, which weigh less than three pounds and are considered disposable, present new, potential problems. Cubesats often utilize none of the maneuvering or deorbiting procedures that have made space safer and cleaner in recent years, and as a result, are creating a new challenge requiring particular attention.*" (Matt Desch, CEO Iridium Communications Inc.)[3]

The CubeSat project, however, does encourage the community to respect the obligations of spacecraft owners and operators to ensure the safety of their own systems, through design and testing. In addition, the need to safeguard the space environment and future access to space is established through the inclusion of debris mitigation requirements within the CubeSat Design Specification (CDS). For instance, the mission design and hardware are required to comply with NASA Procedural Requirements for Limiting Orbital Debris and CubeSat developers need to obtain approval of an orbital debris mitigation plan from the Federal Communication Commission (FCC).[1] A "Deviation Waiver Approval Request" must be submitted if the CubeSat does not meet any of these requirements.

Of particular concern to *all* operators with spacecraft in LEO is the requirement to limit the orbital lifetime remaining after end of the mission. There are many guidelines and standards addressing this requirement, but most recognise that the remaining lifetime should be less than 25-years[*]. Analyses by debris evolutionary models have shown that good compliance with this requirement (e.g. with a probability of 0.9) plays a key role in mitigating the space debris hazard.[4]

In order to comply with the end of mission disposal requirement, the spacecraft must be left in an orbit such that natural perturbations (especially atmospheric drag) will lead to re-entry within 25 years. For spacecraft with manoeuvring capability this can be achieved typically through the expenditure of propellant, which can be budgeted and included at the design stage. However, CubeSats do not currently have such capability and their orbit is dependent upon on the launch vehicle.

In their 2011 paper, Oltrogge and Leveque analysed the lifetimes of CubeSats launched after 2003 and estimated that only 38% of CubeSats launched before 2012 had remaining lifetimes respecting the debris mitigation requirements.[5] Following this work, Qiao et al. suggested that high altitude CubeSats will threaten other spacecraft unless deorbit devices are included.[6]

As a result of their analysis, Oltrogge and Leveque called upon the CubeSat community to take leadership roles in space debris assessment, ensuring that debris guidelines and standards are met and by implementing effective debris mitigation strategies.[5] However, it is clear that misconceptions about the orbital lifetimes, and the risks posed by CubeSats, remain. For example, some common misconceptions arising in media reports and comments made by readers (found through internet searches using keywords "CubeSat orbital debris", "CubeSat altitude", "CubeSat collision" "CubeSat problems") include:

- "*They're very small and because they're generally put into a very low [90-100 km] orbit, they eventually – naturally – de-orbit anyway*."
- "*U.S. CubeSats abide by NASA Procedural Requirements and Technical Standards for limiting orbital debris*"
- "*Most CubeSats are in a relatively low altitude orbit*"
- "*Most CubeSats fly at fairly low altitudes. They will not stay in orbit for decades. Furthermore, their trajectories can be controlled from launch, and they can be tracked fairly easily with radar. We know where they are, and where they are going. Fragmentation due to impacts with other objects is unlikely due to their small size*."
- "*Operational satellites, such as CubeSats, I think should take a back-seat to the discussion [of space debris]*"

At the same time an increasing number of startups and existing companies are looking to constellations of small satellites (smallsats) to meet demands for downstream products. Using their satellite Launch Demand Database (LDDB), SpaceWorks Enterprises Inc. estimated that between 2,000 and 2,750 nano/microsatellites will require a launch from 2014 through 2020 with more than half expected to be provided by the commercial sector.[7] As a result of their recent emergence into the space sector, it is not wholly clear what role these startups will take in the leadership of debris mitigation efforts. However, indications from these emerging space users suggest that they are, at least, aware of the issues.

To provide some clarity, a database of CubeSats containing their launch history and relevant physical parameters has been developed for use within the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE), which has

[*] The 25-year requirement should be seen as the maximum value and, if possible, all available capabilities should be used to minimise the time spent in LEO.

been employed to assess the future collision risk. Concurrently, the database of satellite conjunctions produced by Celestrak's Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES)[8] was examined to assess the impact of CubeSats, in the DAMAGE database, on the population of catalogued space objects from 2005 through 2014.

III DAMAGE CUBESAT DATABASE

The DAMAGE CubeSat database contains information on the orbit and physical characteristics of 165 CubeSats launched between June 2003 and December 2013. For each satellite, the DAMAGE semi-analytical orbital propagator was used to estimate the orbital lifetime. The propagator includes natural perturbations from Earth gravity harmonics (J_2, J_3), atmospheric drag, third-body gravitational forces (Moon, Sun) and solar radiation pressure. The physical properties of the satellites (area, mass) were derived from internet searches or, where this information was unavailable, from the CubeSat form factor under the assumption that 1U = 1 kg and 10×10×10 cm. The mean cross-sectional area (for estimating drag and collision cross-section) was determined using Oltrogge and Leveque's method[5]:

$$CSA = \frac{1}{2}[S_1 + S_2 + \cdots + S_6], \quad [1]$$

where $S_{i=1\ldots6}$ is the surface area of side *i* on the CubeSat.

CubeSat ballistic coefficients were estimated using the DAMAGE Adaptive Re-entry Tool (DART), which fits a linear model to re-entry predictions derived from the time-series of Two-Line Element (TLE) data for individual satellites, to optimise the ballistic coefficient estimate. Not all CubeSats in the database had recorded TLE data and DART predictions for some CubeSats did no converge on a stable ballistic coefficient estimate.

Finally, entries in the DAMAGE CubeSat database were correlated with the corresponding entries in the SOCRATES database and any conjunctions involving those satellites were identified and added to the analysis. Each SOCRATES report provides information on pending conjunctions on orbit over the coming week and the system produces reports twice each day (three times each day since late 2013). Each report consists of a list of conjunctions < 5 km for all satellite payloads on orbit against all objects on orbit using the catalogue of unclassified NORAD TLE data.[8] These lists were filtered to remove duplicate conjunctions.

Fig. II shows the cumulative number of CubeSats launched (black), correlated with entries in the SOCRATES database (red), and for which a ballistic coefficient was determined using DART (blue), over time. DART was able to generate orbital lifetimes for 67% of the launched satellites. In addition, 71% of the satellites in the DAMAGE database were correlated with CubeSats in the SOCRATES database. Fig. II also shows the cumulative number of CubeSats in the database with remaining lifetimes > 1 year (green), > 10 years (orange), and > 25 years (dark red). Based on these data, 34% of the CubeSats in the database with estimated ballistic coefficients have orbital lifetimes greater than 25 years.

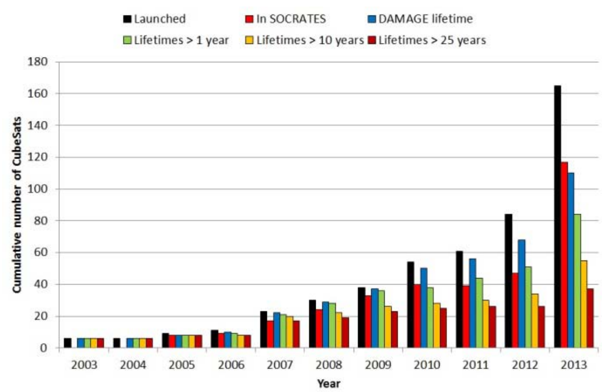

Fig. II: Analysis of the DAMAGE CubeSat database.

With respect to the conjunctions identified by SOCRATES, there were 363,384 conjunctions < 5 km involving CubeSats from the database in the period November 2005 through June 2014 (Tab. I). The average number of conjunctions per CubeSat was 2,229 over this period. 88% of the CubeSats experiencing more than 5000 conjunctions were also in orbits with estimated remaining orbital lifetimes > 25 years.

Total number of conjunctions	90,536,935
Conjunctions involving CubeSats	1,980,668
Filtered conjunctions involving CubeSats	363,384
Maximum cumulative number of filtered conjunctions for individual CubeSat	17,112
Average cumulative number of filtered conjunctions for individual CubeSat	2,229

Table I: SOCRATES analysis November 2005-June 2014

The cumulative number of conjunctions involving CubeSats increased exponentially over the SOCRATES reporting period (Fig. III), resulting in 79,996 conjunctions in the first half of 2014 (corresponding to an average 95 conjunctions per month and per satellite), compared with 41,157 for the 12 months of 2010. At the same time, the proportion of all conjunctions listed by SOCRATES that involved CubeSats grew from 1-in-100 in the year 2007, to 1-in-20 in the first six months of 2014 (Fig. IV).

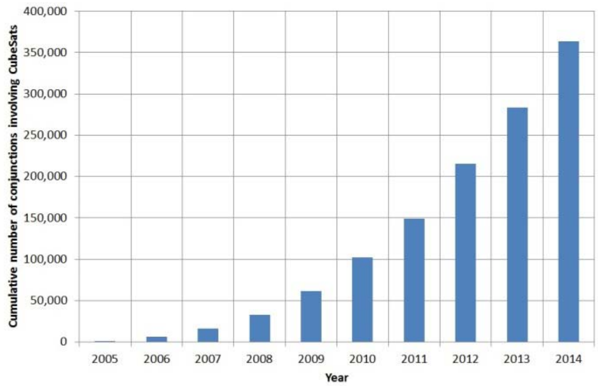

Fig. III: Cumulative number of conjunctions involving CubeSats from the SOCRATES database.

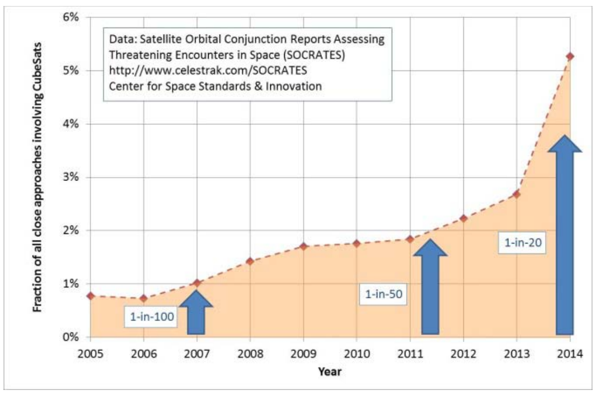

Fig. IV: Fraction of all conjunctions in SOCRATES that involved CubeSats from the database as a function of time.

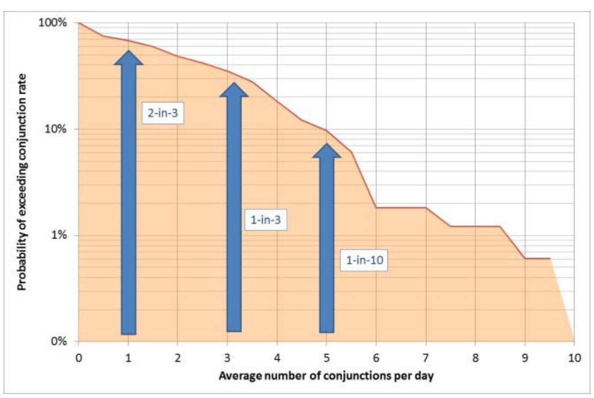

Fig. V: Cumulative probability distribution showing the average conjunction rate experienced by a typical CubeSat.

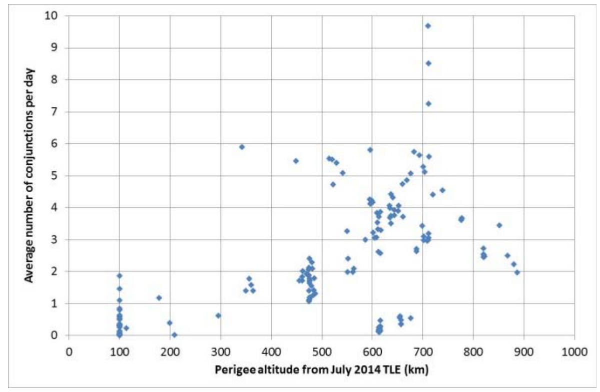

Fig. VI: Average number of conjunctions in SOCRATES per day for individual CubeSats as a function of their perigee altitude (calculated from July 2014 TLEs).

Over their orbital lifetime, two-thirds of all CubeSats in the database have experienced one conjunction per day, one-third have experienced three conjunctions per day and one-tenth have experienced five conjunctions per day (Fig. V). Some CubeSats have been involved in more than nine conjunctions per day, on average, over their lifetime.

Given the non-uniform distribution in altitude of catalogued objects it is, perhaps, likely that some CubeSats have been involved in more conjunctions due to the orbit provided by the launch vehicle. An analysis of the perigee altitudes of the CubeSats in the DAMAGE database (perigees determined from June 2014 TLE data) revealed that many CubeSats between 600 km and 800 km altitude experienced more than three conjunctions per day, on average, although some CubeSats at lower altitudes (e.g. at 400 km) have experienced more than five conjunctions per day.

Given the large number of conjunctions that has already been seen by the increasing population of CubeSats, it is highly probable that the continued growth of the CubeSat and smallsat populations – to meet the predicted market demands – will lead to rapidly increasing collision hazards unless appropriate mitigation measures are implemented.

III. CUBESAT RISK ASSESSMENT USING DAMAGE

The University of Southampton's debris model, DAMAGE, is a three-dimensional evolutionary model of the full LEO to Geosynchronous space debris environment. DAMAGE is a semi-deterministic model implemented in C++ and runs under Microsoft Windows. It includes a semi-analytical orbital propagator and a fast, target-based collision algorithm that employs a stochastic approach to estimate collision probabilities over the projection period and multiple runs. A Monte Carlo (MC) simulation approach is used to estimate the future LEO population and collision probability distributions, from which statistics can be derived to describe the future environment.

For this work, the initial population of objects ≥ 10 cm residing or crossing the LEO region on 1 January 2013, and historical launch traffic 2005 through 2012 from the European Space Agency's (ESA's) Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model, were used as the basis for future projections. To reduce the many degrees of freedom within the model, the following assumptions were made: future launch traffic, excluding CubeSats, was represented by repeating the historical launch traffic cycle, spacecraft and rocket bodies were moved immediately to decay orbits with lifetimes < 25 years after the end of their operational life (assumed to be eight years from launch) and with 90% compliance, and no explosions were allowed. The resulting debris environment was evolved at five-day intervals from the reference epoch 1 January 2013 to 1 January 2043.

In addition to the "baseline" scenario described above, three further DAMAGE scenarios were developed to account for differing CubeSat launch rates, *L*, from 2013 to the year 2043, according to three Gompertz logistic curves,

$$L = \mathrm{int}\left[ae^{-be^{c(t-t_0)}} + 0.5\right], \qquad [2]$$

where "int" returns an integer value and the coefficients are defined in Tab. II.

Coefficient	Low	Medium	High
a	205	560	700
b	2260	21.5	135
c	0.8	0.25	0.42
t_0	2003	2003	2003

Table II: Gompertz logistic function coefficients used to estimate future CubeSat launch traffic.

The Gompertz logistic function captures the fast, initial growth in CubeSat launches (e.g. from 2003 to the present) followed by a steady increase and then convergence to a constant launch rate (Fig. VII). The three CubeSat launch traffic scenarions, "low", "medium" and "high", and the corresponding asymptotes, were chosen to reflect the uncertainty in the expected growth of CubeSat/smallsat activities but the real launch rates may be lower or higher. However, the coefficients for the "medium" launch traffic scenario were selected to produce launch rates for the period 2014-2020 consistent with those predicted by SpaceWorks Enterprises Inc.[7] Whilst many planned smallsat missions are not CubeSats, the assumption used for this work was that future smallsat launches could be represented by CubeSats in the DAMAGE database.

The CubeSat launch traffic profiles described by Eq. 2 were recorded as text files for input to DAMAGE. For each projection year, DAMAGE read the launch rate from the file and generated the correct number of CubeSat launches. Launch vehicles were assumed to re-enter immediately after deployment of the CubeSats. Orbital and physical characteristics for each CubeSat were determined by selecting at random from the CubeSats in the DAMAGE database. To ensure sufficient distribution in the orbital elements (and prevent collisions between CubeSats at launch), the right ascension of the ascending node, argument of perigee and mean anomaly were randomised in the range [0, 360]°. In addition, a random value in the range [-50, +50] km was added to the perigee altitude, and another in the range [-0.5, +0.5]° was added to the inclination.

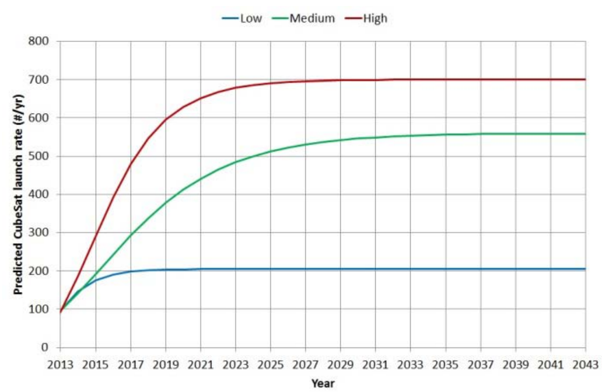

Fig. VII: Estimates of future CubeSat launches for three traffic scenarios: low, medium and high launch rates.

Finally, an Effective Population Increase Factor (EPIF) was used to determine the impact of the CubeSats on the LEO debris population,

$$\mathrm{EPIF}(t) = \frac{N_{S,T}(t) - N_{1,T}(t)}{N_{S,C}} - 1. \qquad [3]$$

Here, $N_{S,T}(t)$ is the average number of objects ≥ 10 cm in the environment at time *t*, for a scenario, *S*, involving CubeSat launches. $N_{1,T}(t)$ is the average number of objects at time *t* for the baseline scenario (i.e. without CubeSat launches), and $N_{S,C}$ is the number of CubeSats on-orbit at time *t* in scenario *S*. The EPIF describes the effective number of additional objects added to the LEO population per CubeSat. This metric also accounts for the CubeSats themselves: any EPIF value > 0 represents a net increase in the population in addition to the CubeSats.

IV. RESULTS

The future LEO population and collision probability distributions were estimated by DAMAGE for each of the four launch traffic scenarios using 100 MC runs (per scenario). Fig VIII shows the resulting population probability distributions for the "baseline" (top) and "medium" (bottom) scenarios. The colours used in Fig. VIII represent different probability levels, determined from the MC runs. For example, the probability that the number of objects was greater than or equal to 20,000 on 1 January 2043 is 0.24 without CubeSat launches (i.e. 24 MC runs out of 100), or 0.98 if CubeSat launch traffic follows the "medium" scenario (i.e. 98 MC runs out of 100).

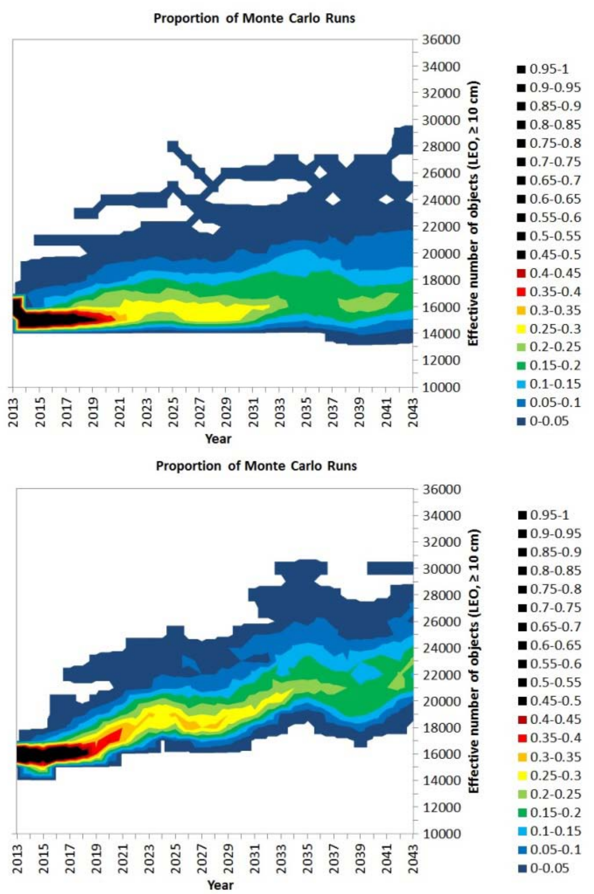

Fig. VIII: Probability density distributions estimated from 100 MC runs showing the effective number of objects ≥ 10 cm in LEO as a function of time: no CubeSat launches (top) and with CubeSats at a medium launch rate (bottom).

To make comparisons between the scenarios straightforward, the averages from the probability distributions were used. However, the use of these averages implies a Gaussian probability distribution that was not observed in the MC data (e.g. Fig. VIII). As such, the reader is cautioned about drawing particular conclusions from the following results.

The effects of the differing CubeSat launch traffic scenarios on the (average) future debris populations are shown in Fig. IX. The regular change in the gradient of the curves shown was due to the pseudo-sinusoidal solar activity assumed over the projection period. The average number of objects ≥ 10 cm in LEO for the scenario without new CubeSat launches, was 18,749 at the end of the projection period. In contrast, CubeSat launch activity increased the population to 20,877 objects, on average, for the "low" launch rate, and to 25,003 objects, on average, for the "high" launch rate.

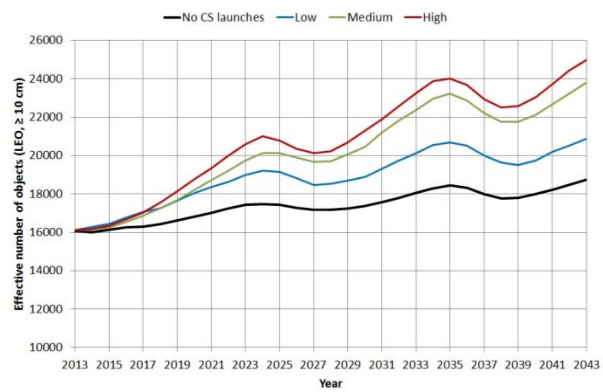

Fig. IX: Average number of objects ≥ 10 cm in LEO as a function of time, for four CubeSat traffic scenarios: no CubeSat launches, and low, medium and high CubeSat launch rates.

Across the full projection period, 6133 CubeSats were launched in the "low" launch rate scenario with 1731 (28.2%) remaining in orbit by 1 January 2043, on average. For the "medium" launch rate scenario, 14,409 CubeSats were launched and 4389 (30.5%) were remaining in orbit by 1 January 2043, on average. Finally, 19,172 CubeSats were launched in the "high" launch rate scenario and 5657 (29.5%) remained in orbit on 1 January 2043, on average. In the "medium" launch traffic scenario, the average number of CubeSats in the environment was the same as the average number of collision fragments generated over the projection period. In addition, CubeSats accounted for nearly half of all intact objects in LEO by 1 January 2043.

Fig. X shows the cumulative number of conjunctions involving CubeSats, and the cumulative collision probability, for the three Cubesat launch traffic scenarios. The collision probabilities shown represent the expected number of collisions. For comparison, the corresponding number of conjunctions and collision probabilities are also shown for Envisat and for all objects. In DAMAGE, conjunctions were defined as close approaches within 17 km (actually $\sqrt{300}$ km).

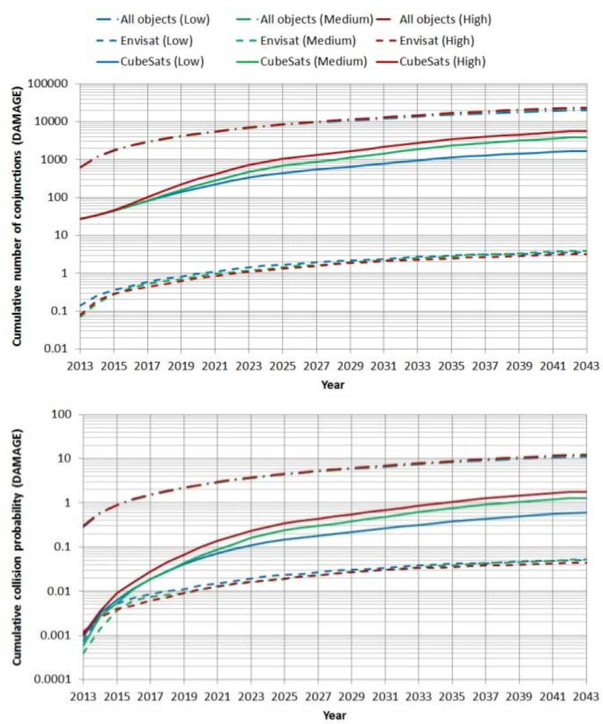

Fig. X: Average cumulative number of conjunctions (top) and collision probability/number of collisions (bottom) as a function of time for all objects, Envisat and CubeSats in three traffic scenarios.

As DAMAGE employs a five-day time-step to evolve the debris population and then a "sampling-in-time" approach to identify any conjunctions, the number of events shown in Fig. X is not an accurate reflection of the likely true number of conjunctions. Recall that the SOCRATES database lists more than 360,000 conjunctions involving CubeSats over the period 2005 to 2014 (Tab. I). However, the ratio of the number of conjunctions involving CubeSats to the total number of conjunctions for all objects can be used as a more reliable indicator (Fig. XI). In contrast, the estimates of the collision probability made by DAMAGE were considered to be reliable (under the stated assumptions), as the effects of the time-step and the sampling-in-time process are taken into account in the calculation of the probability.[9]

The cumulative number of conjunctions recorded by DAMAGE was between 19,988 and 23,409 for the "low" and "high" CubeSat launch rates, respectively. Conjunctions involving Envisat accounted for only three, whereas CubeSats accounted, collectively, for between 1674 and 5542, on average. The resulting collision probabilities suggested that up to two collisions involving CubeSats might occur, on average, in a total of 10 over the projection period (Fig. X).

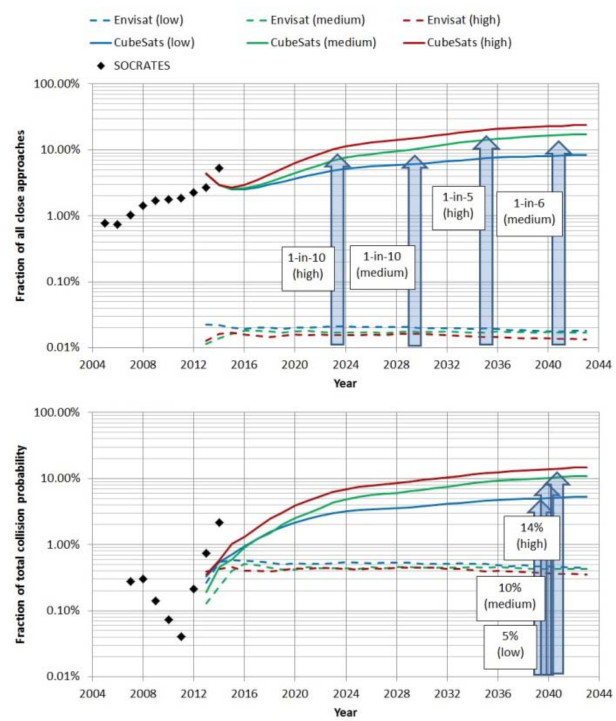

Fig. XI: Fraction of total conjunctions (top) and collision probability (bottom) involving Envisat or CubeSats in three traffic scenarios. Data from SOCRATES for historical CubeSat activity is also shown.

By 2023, one in every 10 conjunctions recorded by DAMAGE involved a CubeSat in the "high" launch rate scenario, an increase from about one in every 20 conjunctions at present, as estimated from the SOCRATES data (Fig XI). The number increased to one in every five conjunctions by 2035. By the end of the projection period, CubeSats accounted for 14% of the total environment collision probability in the same scenario. Even in the "low" launch rate scenario, CubeSats accounted for 8% of all conjunctions and 5% of the total collision probability by 2043. For the "medium" launch rate scenario, which reflects the launch rate suggested by SpaceWorks Enterprises Inc., CubeSats accounted for one in every six conjunctions and 10% of the total collision probability.

Using a short historical projection from 1 November 2005 through 1 January 2013, it was possible to build a calibration model relating the conjunctions predicted by DAMAGE to those recorded by SOCRATES and involving CubeSats in the database. In fact, two linear models were produced (A and B in Fig. XII) and used to predict the possible number of "true" conjunctions involving CubeSats over the period 2013 to 2043 (Fig. XIII). Here, the "true" conjunctions refer to those that would likely be predicted by SOCRATES.

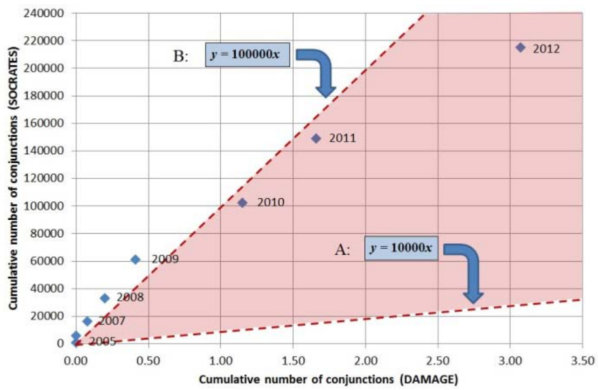

Fig. XII: Calibration based on the cumulative number of conjunctions predicted by DAMAGE and by SOCRATES over the historical projection period 1 November 2005 to 1 January 2013.

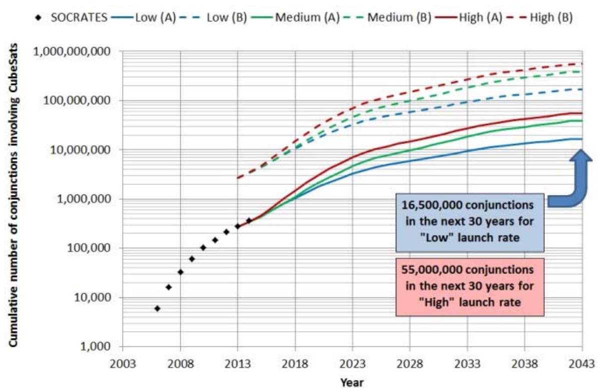

Fig. XIII: Estimates of the "true" cumulative number of conjunctions involving CubeSats from 2013 to 2043 for three CubeSat launch traffic scenarios and two calibration models.

Fig. XIII shows that DAMAGE estimates that CubeSats could be involved in 16.5 million to 550 million conjunctions over the next 30 years, depending on the launch traffic scenario and the assumed calibration model. Based on the historical SOCRATES data (also shown in Fig. XIII), the lower estimates seem more likely although data for 2014 are incomplete.

The EPIF (Eq. 3) was calculated for each of the three CubeSat launch traffic scenarios (Fig. XIV and Tab. III). In all of the scenarios investigated, the CubeSat traffic resulted in additional objects in the LEO environment (over and above the CubeSats themselves). The origin of these objects must have been collisions involving CubeSats. For example, a collision fragment was generated for every 4.4 CubeSats on-orbit in the "low" launch rate scenario, on average.

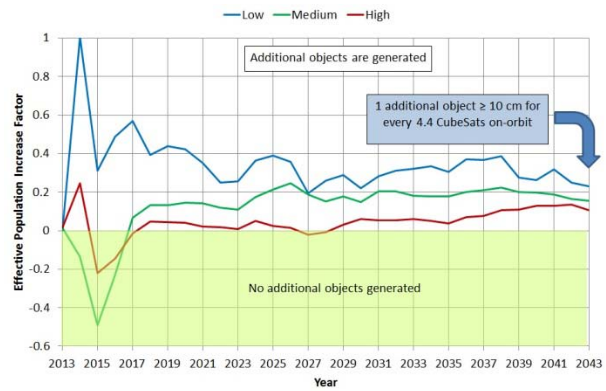

Fig. XIV: Average Effective Population Increase Factor for three CubeSat traffic scenarios.

Scenario	Average EPIF	Standard deviation
Low	0.34	0.16
Medium	0.12	0.15
High	0.04	0.08

Table III: Average EPIF scores for the three CubeSat launch traffic scenarios, with standard deviations.

Given DAMAGE predicted that collisions involving CubeSats would occur during the projection period, it was important to understand the likely characteristics of those collisions.

The stochastic nature of the collision algorithm in DAMAGE is such that any of the conjunctions identified could have resulted in a collision, given sufficient MC runs. Consequently, data about conjuncting object-pairs were used for the assessment of the collision characteristics, rather than performing this assessment only on objects involved in predicted *collisions*. Doing this improved the reliability of the assessment, because relatively large numbers of conjunctions were predicted compared with the number of collisions that were predicted. For this analysis, the term "impactor" was always taken to mean the non-CubeSat conjunction partner.

It was assumed that there were no significant differences in the conjunction characteristics arising from the different launch traffic rates. As such, the conjunctions from the "medium" CubeSat launch traffic scenario were assumed to be suitably representative. All of the conjunctions from 100 DAMAGE MC runs for this scenario were used to build distribution functions for the impactor semi-major axis, eccentricity and inclination (Fig. XV).

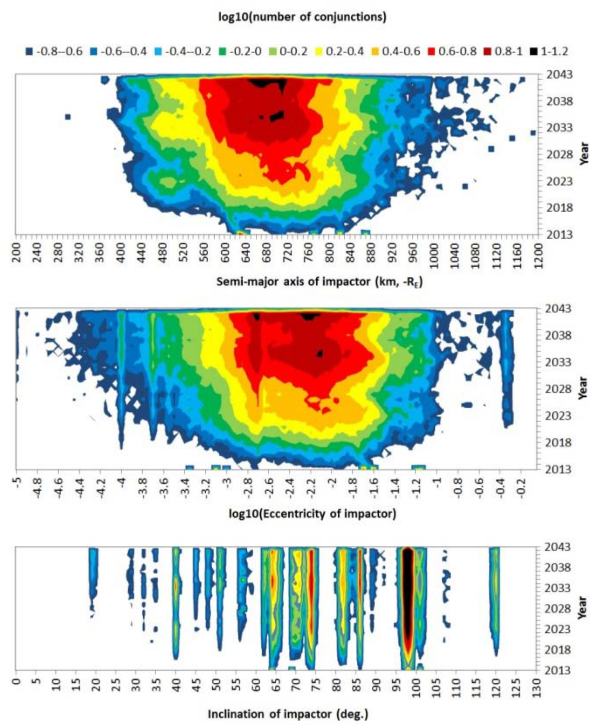

Fig. XV: Density functions showing the distribution of impactor semi-major axis, eccentricity and inclination for all conjunctions involving CubeSats recorded in 100 MC runs and for the medium launch traffic scenario. R_E=6378 km was assumed to be the mean radius of the Earth.

Fig. XV shows that throughout the projection period, impactors with a semi-major axis between R_E +600 km and R_E +800 km were more common. These values coincide with the semi-major axis of popular Sun-synchronous orbits, used by many remote sensing spacecraft. The hypothesis that the orbits of many of the impactors were Sun-synchronous was supported by the distribution of the impactor eccentricities and inclinations, which revealed that eccentricities around 0.005 and inclinations of 98° were most common. However, over time the spreads in possible impactor semi-major axis, eccentricity and inclination increased, with semi-major axis values between R_E +280 km and R_E +1200 km, and inclinations between 17° and 120° being recorded by the end of the projection period.

The analysis of impactor orbits revealed that CubeSats in the DAMAGE simulations were involved in conjunctions and collisions with objects from many different orbital regimes in LEO, although predominantly with objects in Sun-synchronous orbits. No impactor was found on a Geosynchronous Transfer Orbit (GTO).

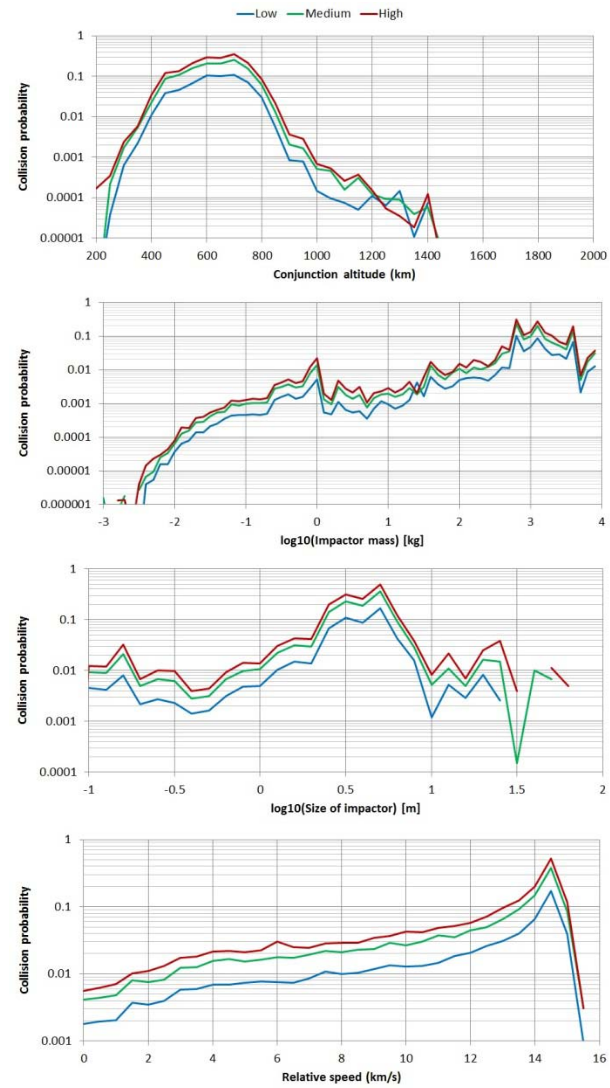

Fig. XVI: Collision probability as a function of the conjunction altitude, impactor mass, size, and relative speed for all conjunctions involving CubeSats recorded in 100 MC runs and for three launch traffic scenarios.

The distribution of the collision probability in terms of the conjunction altitude (Fig. XVI, top), is consistent with the semi-major axis distribution in Fig. XV and with the conjunctions recorded in the SOCRATES database (Fig. VI). The collision probability is maximum for conjunctions at 750 km altitude and is at least an order of magnitude higher there, than at altitudes below 400 km or above 800 km.

Impactor masses were between 3 g and 8000 kg, but objects > 500 kg contributed the highest collision probability. The collision probability associated with impactors < 50 kg (i.e. typical small-satellite range) was two orders of magnitude lower than the maximum probability. Similarly, the maximum collision probability was associated with objects around 5 m in size. At sizes corresponding to typical small satellites, the collision probability was an order of magnitude lower.

Taking the distributions in mass and size with the distribution in the relative speed, the maximum collision probability for conjunctions involving CubeSats likely corresponded with high-speed encounters with large and massive objects. Even with the relatively low masses of the CubeSats, many of these conjunctions had catastrophic energy levels (i.e. kinetic energy exceeding 40 J/g) and would lead to the generation of many fragments in the event of a collision. This observation is consistent with the EPIF results in Fig. XIV.

V. DISCUSSION

Analysis of the SOCRATES database has revealed that many conjunctions involving CubeSats have occurred in the recent past. DAMAGE simulation results presented here have shown that conjunctions are likely to increase even for relatively low launch rates. Some of the conjunctions may result in collisions with large objects in Sun-synchronous orbits and at speeds sufficient to induce the catastrophic breakup of both objects. As such, future scenarios with CubeSat launch traffic in DAMAGE led to a worsening debris environment. In fact, DAMAGE simulations performed for other work have shown that the growth of the LEO population over 30 years seen in the worst-case CubeSat scenario here, would take 200 years without CubeSat traffic under identical conditions.[10]

Even with the relatively low “conversion” of CubeSat conjunctions to collisions, the high proportion of conjunctions involving CubeSats would significantly affect spacecraft operations in the future, given the requirements of collision avoidance. Clearly, the sustainable use of outer space could be jeopardised if the projection of a substantial growth in smallsat launches does materialise and appropriate debris mitigation measures are not taken.

Fortunately, there are a number of measures that can be implemented by CubeSat developers and operators, to mitigate the risks. These include:

- Reducing the time in orbit by changing the planned mission orbit altitude (this may also have the benefit of reducing the expected collision probability);
- Adding de-orbit devices (e.g. drag augmentation devices, such as inflatable balloons, which increase the area-to-mass ratio) to reduce orbital lifetime.

There are still difficulties, however. Changing the planned mission orbit altitude may involve moving to a different launch vehicle. This was done for the UK Space Agency and Clyde Space UKube-1 mission, which was originally manifested on a Dnepr launch with several other CubeSats. Calculations showed that the de-orbit time for UKube-1 was over 35 years after mission end. Consequently, UKube-1 was moved to a Soyuz-2-1b launch vehicle as a secondary payload and launched on 8 July 2014 from the Baikonur Cosmodrome.[11] Not all missions choose to make such a change and some are knowingly released into orbits with lifetimes exceeding 25 years (Fig. II).

If de-orbit or drag enhancement devices are added to reduce the orbit lifetime, there is a need to ensure that such devices will reduce the collision risk of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit.[12] These devices typically result in a larger collision cross-section and, hence, an increase in the collision probability during natural decay; although the duration of the exposure to the debris environment will be reduced. In addition, spacecraft reliability is not 100% so de-orbit devices should be autonomous, ideally, to reduce the chance that a spacecraft failure will result in non-compliance with the disposal requirement. Some CubeSat suppliers have developed such devices specifically for CubeSats.

Finally, all satellites in LEO – not just CubeSats – have the same obligation to de-orbit at end-of-life. In fact, the compliance rates for spacecraft in LEO, generally, remain low.[13] Whilst this work has focused on the challenges of CubeSats, more effort is needed to encourage *all* users of space to implement sustainable practices and debris mitigation measures.

VI. CONCLUSIONS

Analysis of historical conjunction data for CubeSats has identified more than 360,000 close approaches < 5 km involving these satellites since November 2005. An increasing number of CubeSat launches is likely not sustainable unless appropriate debris mitigation measures are implemented. For three different CubeSat launch traffic scenarios without such mitigation, DAMAGE projections suggested 16.5 million to 550 million conjunctions involving CubeSats would occur over the next 30 years. Analysis of these conjunctions showed that the maximum collision probability arose for high-speed encounters with large objects in Sun-synchronous orbits. However, conjunctions with objects in many different LEO orbital regimes were observed. Within the projections, collisions involving CubeSats generated additional objects in numbers up to one fragment for every 4.4 CubeSats on-orbit.

To reduce the risks, some effort is needed to engage with the growing small-satellite community, and to encourage them to contribute to and, ultimately, lead on sustainable practices and debris mitigation activities.

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ACKNOWLEDGEMENTS

The authors would like to thank the ESA Space Debris Office (especially Holger Krag) for the preparation of and permission to use the MASTER reference population, and T.S. Kelso (CSSI) for assistance with and permission to use the SOCRATES data. In addition, thanks go to Alek Lidtke from the University of Southampton and Craig Clark from Clyde Space for very useful discussions and contributions to the paper, and the members of the Inter-Agency Space Debris Coordination Committee Working Groups 2 and 4 for their comments on preliminary results. This work was started within the Alignment of Capability and Capacity for the Objective of Reducing Debris (ACCORD) project (number 262824), funded by the European Union under the Framework Seven Programme.