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Assessment of Evolving Conjunction Risk for Small Satellite Missions

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ABSTRACT

This study presents an assessment of evolving conjunction risk for small satellite missions (5U or smaller) by using the suite of LeoLabs' analytical tools. The aim is to (1) quantify the growth of small satellites population in the low Earth orbit (LEO), (2) assess the impact of on-orbit break-up events and small debris (sub-10 cm) objects on small satellite missions, and (3) present an optimal risk mitigation timeline for small satellite missions, based on conjunction alerts issued in 2023. The global network of S-band radars built and operated by LeoLabs provides a 24/7 data feed to power this assessment and help identify the evolution of this risk. The ability to access this data in near real-time and provide necessary alerts and services to satellite operators significantly enhances operational safety. Thus, a statistical assessment of the risk posed and quantification of the evolution of this risk over mission timeline is important.

Further, understanding the optimal risk mitigation timeline for small satellite missions is critical as these missions have limited on-board resources and knowing the severity of the risk and taking appropriate and timely mitigative action (attitude change or thrusting 'n' days before time of closest approach, i.e., TCA) is paramount. Although the mitigative action (the level and duration of thrusting or the amount of attitude change) is not studied as these specifics often vary based on the event type, the optimal timeline (number of days before TCA) of this mitigative action is reviewed by studying the conjunction events encountered by small satellites.

INTRODUCTION

Satellite operators need accurate and reliable information to efficiently operate and protect their assets. Ensuring safety and integrity of space assets in an increasingly congested Low Earth Orbit (LEO) is a challenge and the solution is comprehensive space situational awareness.

Thus, the role of commercial space situational awareness (SSA) data providers is significant, and it is vital for all space operators to utilize these services to mitigate the potential for in-orbit collisions and ensure safe operations in space.

LeoLabs is a commercial provider of LEO mapping and SSA services with its own global radar network and data platform. LeoLabs' tracking and monitoring delivers high accuracy tracking data products for satellites down to 1U or slightly smaller.[1] Currently, the radar network is comprised of phased-array radars, appropriately located around the globe. LeoLabs' Data Platform offers a variety of products, including radar measurements, orbit determination, and conjunction screening. The aim is to provide continuous, scalable, reliable, transparent, traceable, and insightful solutions to enable space safety.

Figure 1: Aerial view of the two S-band active phased array radars at the West Australian Space Radar (WASR) site in Collie Shire, Western Australia.

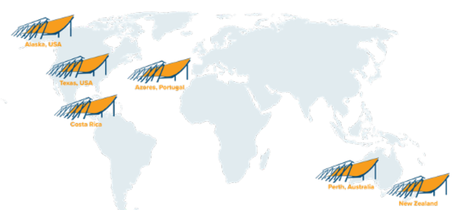

Figure 2: LeoLabs global radar coverage.

WHY SMALL SATELLITES?

Standard CubeSats were first developed in 1999 by California Polytechnic State University at San Luis Obispo (Cal Poly) and Stanford University. These have provided a cost effective platform for education and space exploration.

Small satellites, particularly those up to 5U, have been significant because of the lower cost, rapid development and deployment, ease for conducting technology demonstration and validation, and usefulness for agile and responsive missions. Thus, small satellites now play a crucial role in expanding the capabilities and applications of space technology, fostering innovation, and democratizing access to space. Their smaller size and lower cost open new possibilities for diverse industries, research institutions, and educational institutions to participate in space exploration and utilization.

This study is restricted to small satellites (up to 5U in size) because of the increasing popularity of this size range for recent missions and a plethora of capabilities made possible by these missions. It should be noted the investigation presented here can easily be extended to other subgroups.

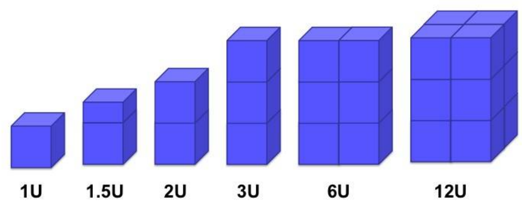

Figure 3: Standard CubeSat sizes. Credits: National Aeronautics and Space Administration (NASA)

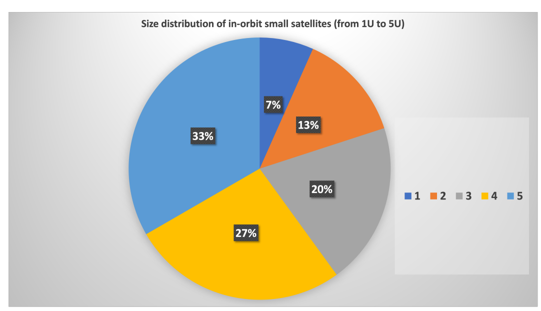

Figure 4: Size distribution of 694 in-orbit small satellites (up to 5U in size).

UPWARD TRAJECTORY

Increased launch activity has enabled easier access to space. In Figure 5, the increase in population of in-orbit small satellites can be distinctly noted. The distribution with respect to average altitude and spatial density across 50 km. altitude bins is shown in Figures 6 and 7 .

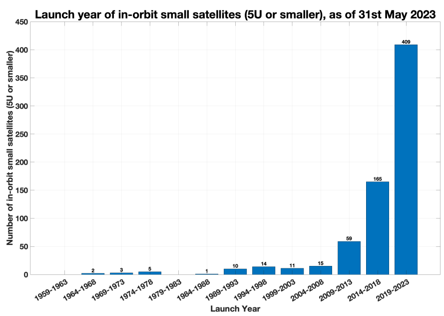

Figure 5: Launch year of in-orbit small satellites (5U or smaller), as of 31st May 2023.

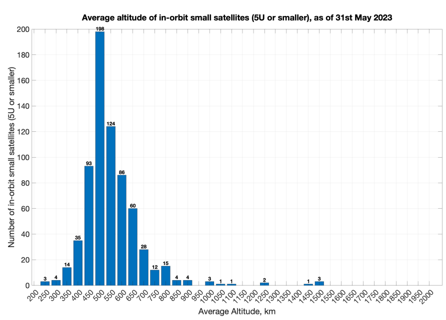

Figure 6: Average altitude of in-orbit small satellites (5U or smaller), as of 31st May 2023.

The population is generally concentrated between 400 and 600 km, respectively. This population mostly consists of operational satellites which can mitigate conjunction risk. Hence, the quantification and evolution of the conjunction risk becomes important for satellite operators to do effective mission planning. In the next section, LeoRisk is used to calculate the statistical collision risk for a simple scenario of a 3U CubeSat.

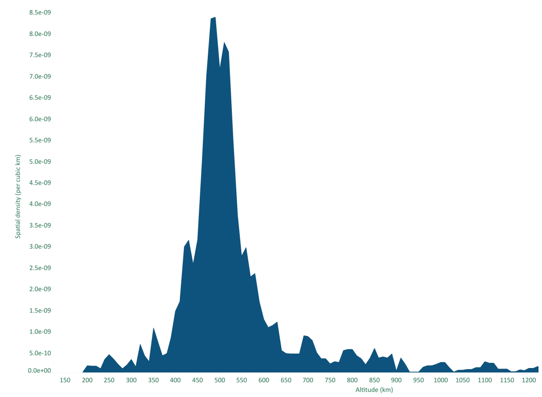

Figure 7: Spatial density of 694 in-orbit small satellites (5U or smaller), as of 31st May 2023

COLLISION AVOIDANCE BURDEN

The collision avoidance burden is studied using LeoRisk, a LeoLabs product quantifying statistical collision risk. This tool enables quantification of collision risk posed to a given satellite or a constellation by applying a physical model leveraging the kinetic theory of gases within a Poisson probability distribution function. The annual probability of collision (Pc) is a function of collision cross-section (i.e., combined for conjuncting objects), relative velocity, and spatial density of the on-orbit population.[2]

A simple scenario of a 3U small satellite in a 400x600 km, 97 deg orbit for a mission lifetime of 5 years, was run and the following charts were generated to summarize the results. For the given scenario, LeoRisk predicts a probability of collision (Pc) of 6.92×10^{-05} in its first year on orbit, see Figure 8. This is a fairly high Pc, however, note that 82.8% of conjunctions in the given altitude range will involve other operational satellites. This is helpful as this makes it a space traffic management problem, where the two operators can discuss their mitigation strategies for risk reduction and is relatively easier to handle than the space debris management, as the derelict objects cannot maneuver and will require a collision avoidance maneuver. When the events involving operational payloads are removed the Pc reduces to 1.60×10^{-05}, see Figure 9.

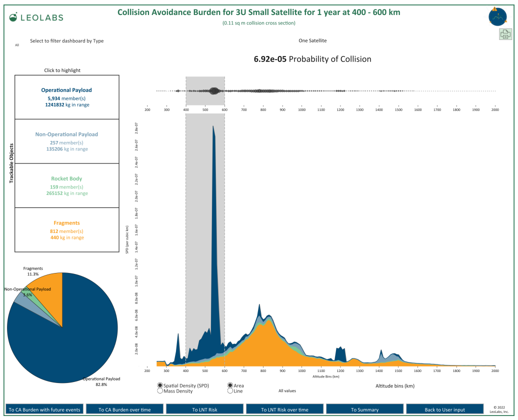

Figure 8: Collision avoidance burden for a 3U CubeSat.

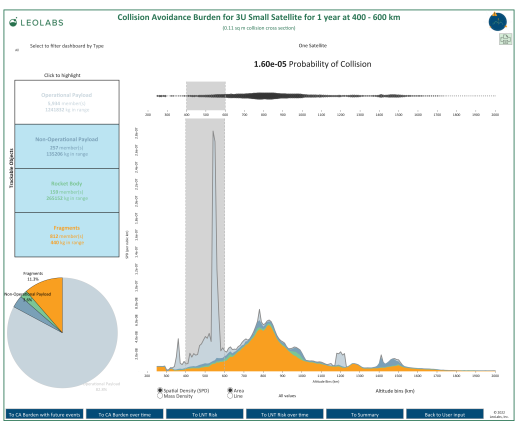

Figure 9: Collision avoidance burden for a 3U CubeSat, due to derelict objects only.

To illustrate the evolution of collision avoidance burden, the LEO population was augmented by linearly adding debris from 2 highly likely future breakup events, selected by an analysis of the 700,000 high-risk PC events over the last 18 months. The evolution of collision avoidance (CA) burden over time is shown in Figure 10 where the accumulation of risk over time is indicated due to existing and added in-orbit debris population.[3,4]

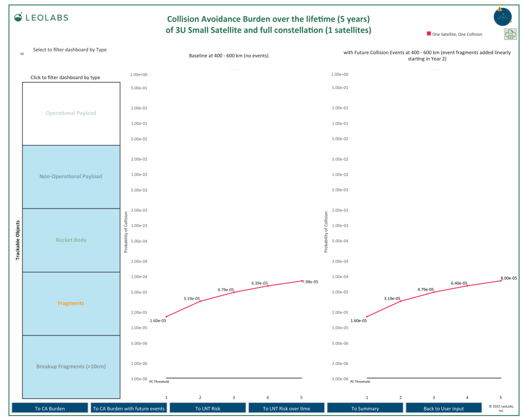

Figure 10: Aggregated collision avoidance burden for a 3U CubeSat over 5 year mission lifetime, due to existing & new derelict objects only.

The risk posed by a statistical population of small debris is evaluated using European Space Agencies' MASTER model. The output from MASTER is integrated in the LeoRisk and is shown in Figure 11.[5]

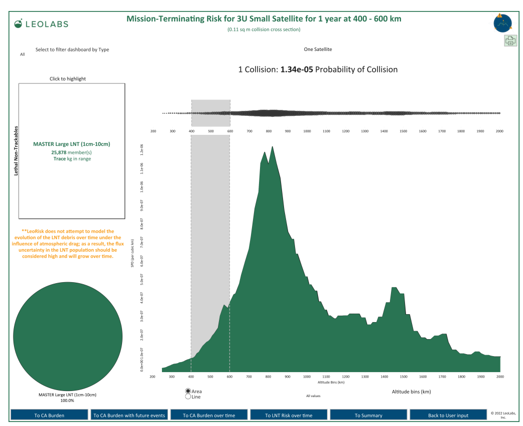

Figure 11: Increase in conjunction avoidance burden due to small debris (sub-10 cm) for a 3U CubeSat.

The smaller cross-section of the small satellites definitely helps, however their agility depends on the on-board propulsion system and perturbations due to atmospheric drag. Thus, during mitigation of an upcoming conjunction, the decision to Go or NoGo is dependent on how far is time of closest approach (TCA) and the latest conjunction assessment on an operator's screen. Mitigative strategies and timelines varies for different operators, primarily based on the mission requirements and on-board propulsion system.

In the next section, a mitigation timeline is suggested based on the conjunction alerts generated this year (from 1st Jan to 15th June 2023) for small satellites with limited maneuvering capability.

MITIGATION TIMELINE

NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook highlights three phases of CA process[6] :

1. CA screenings - To identify close approaches between the primary satellite and secondary objects.
2. CA risk assessment - To examine each of the close approaches produced by the screening activity to determine which may represent dangerous situations and therefore require a mitigative action.
3. CA mitigation – To plan and timely execute a mitigative action, which usually involves a trajectory change for the primary object to reduce the collision risk of the close approach to an acceptable threshold.

Based on the analysis of the conjunction alerts generated for small satellites during 2023, it has been noted that the majority of high-risk events are accurately identified within 3-4 days before TCA, and hence reliable and accurate actions can be taken this far in advance to mitigate the associated risk. TCA-3 days appears to be a good point for these objects to change their attitude or use on-board propulsion system to do collision avoidance. Although, for objects with better propulsion systems on-board, the maneuver decision could be deferred to TCA-36 hours. Of course, two factors that significantly influence a Go/NoGo decision are

1. How much to maneuver to effectively mitigate the risk, and
2. How realistic is the latest conjunction assessment

While the first factor varies for each event and propulsion capabilities of the satellite, the second factor can be assessed.

To understand the second factor better, a subset of relevant conjunction events are isolated from the group of high-risk conjunction events generated, for 694 in-orbit small satellites, during the period of 1st Jan to 15th June 2023. Both a high-risk conjunction event and a relevant conjunction event is defined based on the thresholds for miss distance, Pc, and CDM count. The difference is that a high-risk conjunction event has Pc/miss distance thresholds (Pc $>= 10^{-12}$, Miss distance $<= 10$ km) such that a satellite operator will typically start monitoring the given event, whereas a relevant conjunction alert is a well-tracked event (frequent conjunction data messages) with Pc/miss distance thresholds (Pc $>= 10^{-10}$, Miss distance $<= 1$ km) such that a satellite operator will start planning a risk reduction maneuver for the given event. These relevant events were analyzed to understand when relative to time of closest approach (TCA) did the LeoLabs platform have a realistic solution that could have been used by operators to make a Go/NoGo decision. The heat maps shown in Figures 12 and 13 highlight the variation in miss distance and probability of collision versus the days to TCA. The total CDM count for each block in the heat map is shown in the color bar. There is a clear shift in CDM (conjunction data message) count happening around TCA-3 day period, where majority of CDMs for each event are created and a realistic assessment is provided. Hence, TCA-3 days is a reasonable point for operators to make a Go/NoGo decision. Note, this result matches the conclusions drawn in the 2021 study published by LeoLabs and Planet Labs where Flock constellation was studied and an in-orbit experiment was conducted.[7]

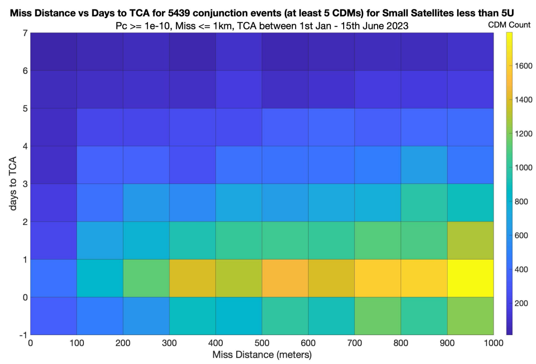

Figure 12: Heat map of the miss distance versus days to TCA (time of closest approach) for selected 5,439 relevant conjunction events, with at least 5 CDMs, Pc >= 10^{-10}, Miss distance <= 1 km, and TCA between 1st January and 15th June 2023.

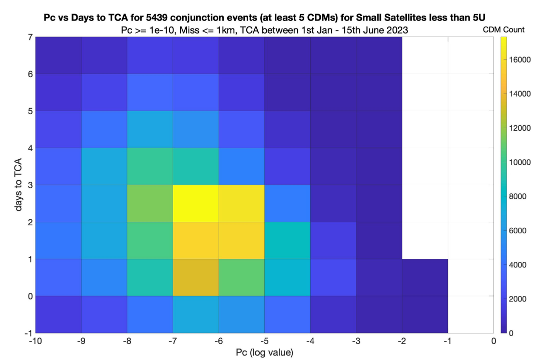

Figure 13: Heat map of the Probability of Collision (Pc) versus days to TCA (time of closest approach) for selected 5,439 relevant conjunction events, with at least 5 CDMs, Pc >= 10^{-10}, Miss distance <= 1 km, and TCA between 1st January and 15th June 2023.

Further, the general distribution of the miss distance and probability of collision for all high-risk conjunction events are shown in Figures 14 and 15 respectively.

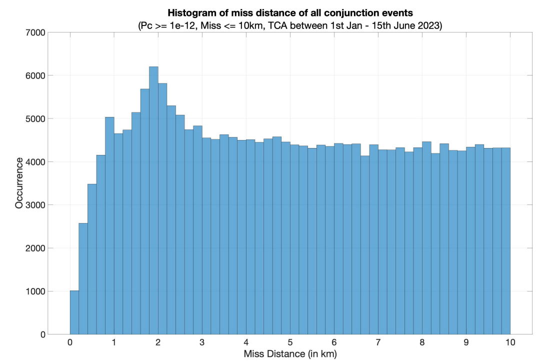

Figure 14: Miss distance distribution for about 222,000 high-risk conjunction events, with Pc >= 10^{-12}, Miss distance <= 10 km, and time of closest approach (TCA) between 1st January and 15th June 2023.

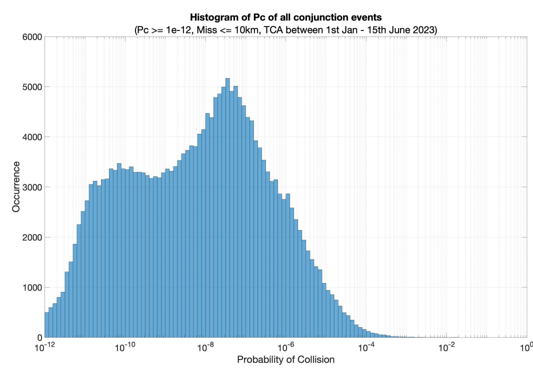

Figure 15: Probability of Collision (Pc) distribution for about 222,000 high-risk conjunction events, with Pc >= 10^{-12}, Miss distance <= 10 km, and time of closest approach (TCA) between 1st January and 15th June 2023.

CONCLUSION

This study presented the benefits of having a complete historical record of over 700,000 conjunction events over last 18 months. The enablement of a huge repository of reliable conjunctions processed in near-real time makes it possible to derive useful insights that can be effective in investigating specific impacts on different subgroups. Because the overall problem of managing the increasing population in LEO is so complex, identifying and categorizing the overall population into smaller subgroups and quantifying the collision avoidance burden and conjunction risk for each of these sub-groups can be an effective strategy.

In this paper, small satellites (up to 5U in size) were studied and an example scenario was modeled to quantify the collision avoidance burden on a 3U CubeSat. Using this scenario and analysis of all high risk conjunction alerts generated over last 6 months for small satellites (5U or smaller), a generic mitigation timeline has been presented. Based on the relevant conjunction alerts generated for 694 in-orbit small satellites, during the period of 1st Jan to 15th June 2023, it was determined that TCA-3 days is a reasonable point for operators to make a Go/NoGo decision as by this time a realistic assessment can be made for most events.

References

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