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Evaluation of LEO conjunction rates using historical flight safety systems and analytical algorithms

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Abstract

In Low Earth Orbit (LEO), satellite operators typically assess the need for a collision avoidance maneuver based upon when one of their satellites is expected to come within 1 kilometre of another space object. In this paper, we compare normalized conjunction statistics extracted from the SOCRATES and Space Data Center historical conjunction assessment archives with a volumetric encounter algorithm characterization to explore historical trends and project future requirements for collision avoidance maneuvers.

Based upon these comparisons, we found that SDC and SOCRATES data indicate that in 2017, LEO spacecraft likely came within 1 kilometre of other objects an average of 2,000 times per month. Now, it's closer to 4,000 average monthly conjunctions. For certain orbit regimes and satellite operators, conjunction alerts may be increasing even faster. In addition, the risk of fratricide encounter, were an event disruptive to satellite control on a large scale to occur, is experiencing dramatic growth as new large constellations become operational.
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Keywords: Close approach, encounter frequency, maneuver notification rate, collision risk

Acronyms/Abbreviations

International Space Station (ISS).

Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES)

1. Introduction

When designing and operating spacecraft in Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO), it is important to ensure that the spacecraft will have sufficient maneuvering propellant and thrust acceleration capabilities commensurate with the expected Space Situational Awareness (SSA) warning time and positional accuracy to effectively avoid collision with other resident space objects.

In Low Earth Orbit (LEO) for example, satellite operators typically assess the need for a collision avoidance maneuver based upon when one of their satellites is expected to come within 1 kilometre of another space object.

In this paper, we assess normalized conjunction statistics extracted from the SOCRATES and Space Data Center historical conjunction assessment archives to explore historical trends and project future requirements for collision avoidance maneuvers. The results of this characterization were first published in the periodical SpaceNews on 19 October 2020 [1].

We then compared these historical results with analytical estimates generated using COMSPOC's volumetric encounter algorithm using the public space TLE catalogue with epochs of 2017, 2020, and 2021.

2. LEO encounter rate estimation using SOCRATES data

The first of our historical conjunction archives is the Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES) [2]. The SOCRATES system uses Systems Tool Kit (STK) to detect all conjunctions of both active and dead payloads in all orbital regimes. SOCRATES identifies conjunction risks as a free public service since 2005. SOCRATES is hosted on the CelesTrak site [3]. Others [4] have found the SOCRATES data to be useful in characterizing encounter rates for select large constellations.

To accomplish this study, the SOCRATES historical archives were used going back to 2006. The goal of this study is to assess how conjunction rates for the active spacecraft population are evolving. Unfortunately, SOCRATES detects conjunctions for all payloads (irrespective of whether they are currently active or dead) in all orbital regimes. While this is less than ideal or exact, we can develop a representative mapping relationship between the SOCRATES weekly 5 km encounters for all (active + dead) payloads to an estimated monthly 1 km encounter rate for only LEO active satellites as shown in Equation 1.

The first scale factor of Equation 1, the square of the ratio between desired and employed keep out radii, is based upon the idealized kinetic theory of gasses and assumes a homogeneous density between where the active spacecraft are currently located and the regions occupied by the combination of active and dead payloads. Once again, while this is less than ideal or exact relationship, it has been demonstrated to be representative [5].

The number of LEO-to-total encounters experienced, based upon independent examinations of LEO [6] and GEO [7] encounter rate research, is nearly 1.0. For this study, based upon per-spacecraft Space Data Center statistics, a ratio of 0.9985 was adopted.

To estimate the final term in Equation 1, it is necessary to estimate the ratio between the number of LEO active spacecraft to the total number of payloads (both dead and alive). The denominator of this ratio is taken directly from the SOCRATES results, as characterized by the green dotted line in Fig. 1. The total size of the catalogue, while not required in Equation 1, is of interest because, as we will soon see, the number of conjunctions scales with catalogue population size. The trends highlight critical events in the evolution of payloads and the space debris population, chiefly the ASAT intercept of the Fengyun spacecraft in 2007, and the Iridium/Cosmos collision of 2009.

Reflected but not expressly shown in Fig. 1 is that 1,763 active spacecraft have been added to the space catalogue in just the last twelve months.

With estimates for all the terms in Equation 1 now in hand, it is possible to map the native SOCRATES weekly 5 km encounter rate for all dead and active payloads to a monthly LEO active satellite 1 km encounter rate as shown in Fig. 2. This result will be compared with other results later.

$$ER_{monthly\ 1\ km\ LEO\ active} = ER_{wk\ 5\ km\ all\ active+dead}\left[\frac{1\ km}{5\ km}\right]^2\left[\frac{30.48\ days}{7\ days}\right]\left[\frac{\#\ LEO\ encounters}{\#\ total\ encounters}\right]\left[\frac{\#\ LEO\ active\ S/C}{\#\ payloads\ (dead+active)}\right] \quad (1)$$

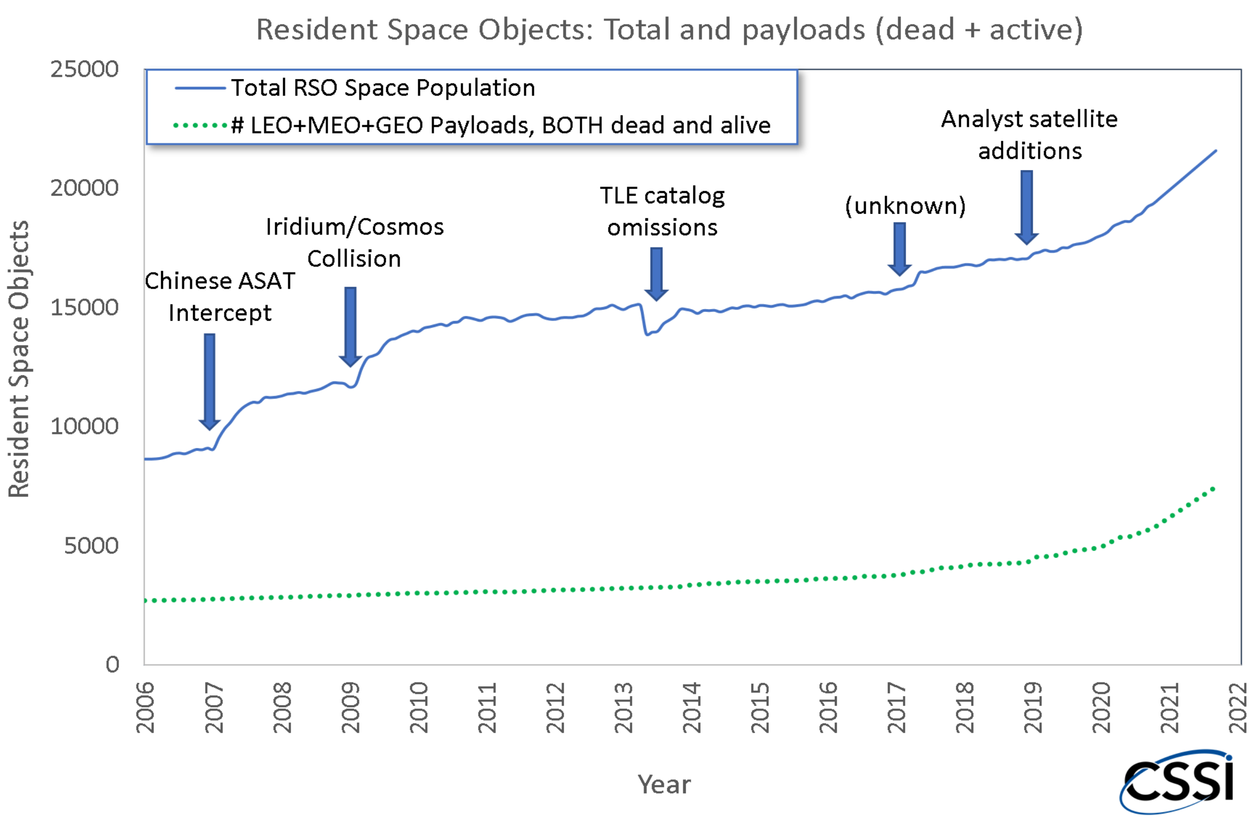


Fig. 1. Evolution of public space catalogue and (dead + active) payload population

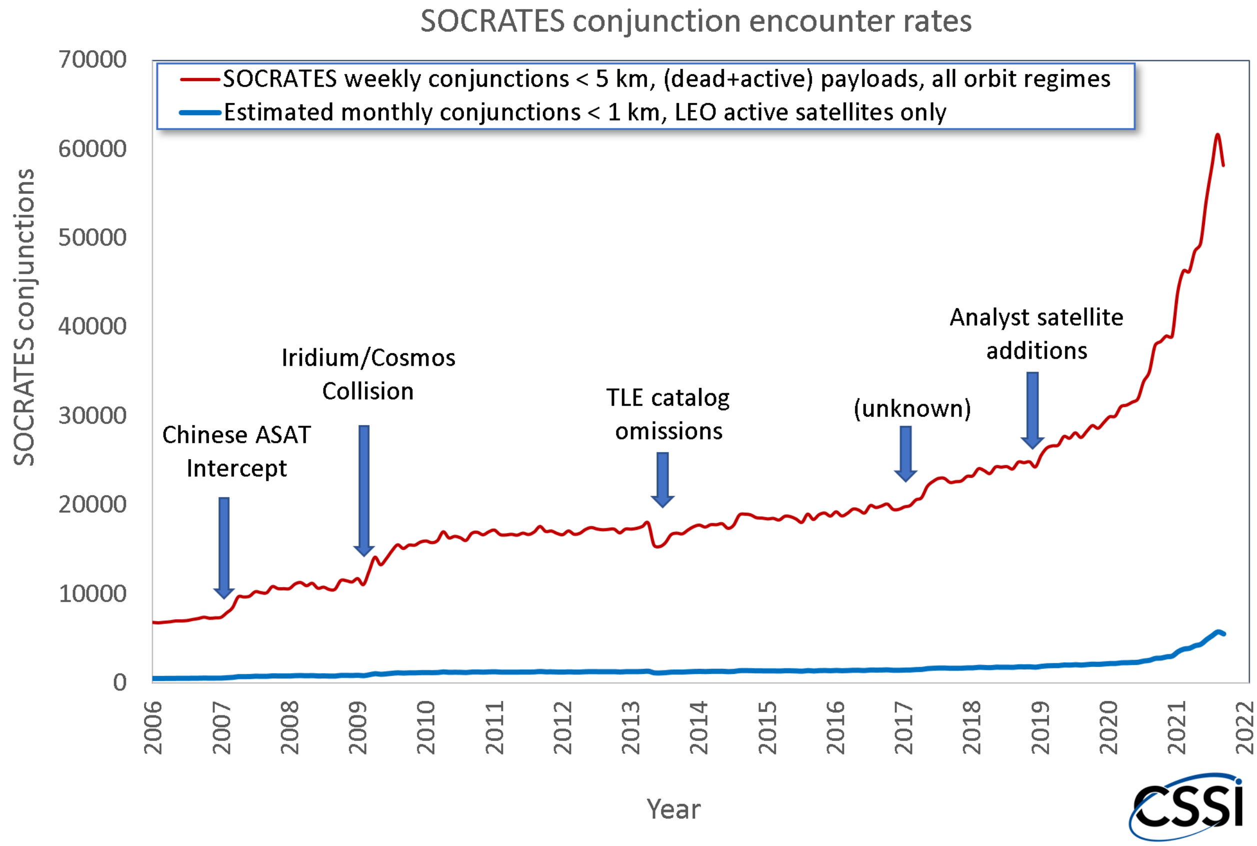


Fig. 2. Evolution of public space catalogue and (dead + active) payload population

3. LEO encounter rate estimation using Space Data Association (SDA) data

The second historical archive data source is the Space Data Center (SDC) [8], operated by COMSPOC for the Space Data Association (SDA) since 2010. The SDA is a non-profit international organization that brings together major satellite companies to contribute towards the safety of space operations and maintaining the integrity of the space environment. The SDC ingests comprehensive spacecraft operator data, normalizes it, and compares it with U.S. government orbit solutions for the rest of the tracked space object population to assess conjunction risks and warn satellite operators. Historical SDC data was incorporated into this study for the period 2016 to October 2020.

When SDC data was collected for this study in October 2020, the SDA had 347 LEO and Middle Earth Orbit (MEO) active satellites enrolled in the SDC's conjunction assessment service, with 20 of those belonging to O3B (a MEO constellation). As a result, there were 327 active LEO satellites in the service prior to October 2020.

The conjunction rates for SDA LEO and GEO spacecraft are shown in Fig. 3. It is noteworthy that the GEO conjunction rates have been fairly constant, which is not too surprising since the GEO population (and number of assigned ITU orbital slots) has not changed appreciably over many decades.

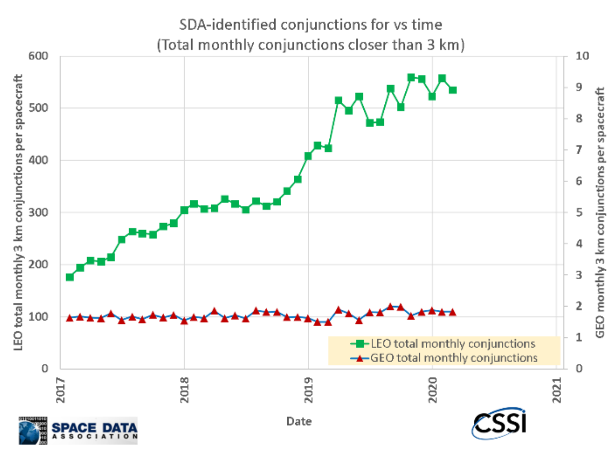


Fig. 3. SDA LEO and GEO monthly < 3 km conjunction rates

spacecraft criteria used for the SOCRATES data, it may be of interest to examine how the per-spacecraft conjunction rate is evolving in addition to the total number of conjunctions. The per-spacecraft LEO active 3 km encounter rate is depicted alongside the RSO space population growth trends in Fig. 4. Note the roughly 20% increase in encounter rates (left-hand y-axis) on this per-spacecraft basis, which mirrors the roughly 20% growth in the catalogue (right-hand y-axis) during a four-year period.

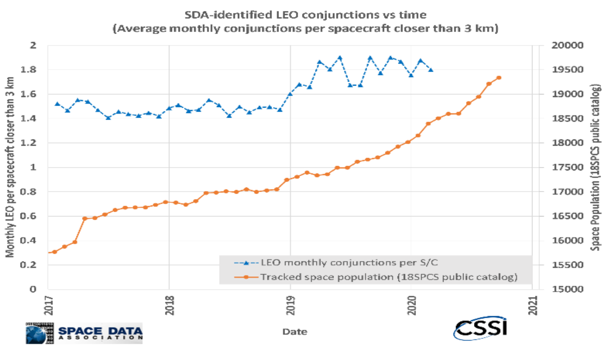


Fig. 4. SDA LEO and GEO monthly < 3 km conjunction rates

We are now positioned to combine the SOCRATES and SDA data onto a single normalized plot as shown in Fig. 5. While the two trends are not an exact match, their growth rates at least mirror and are consistent with each other considering the approximations required to accomplish this normalization and the close match in growth rate of the two trends.

In terms of the offset between SOCRATES and SDC profiles, there are several likely explanations for why the scaled SDC data may not accurately reflect conjunctions rates for the entire population of LEO satellites: (1) SDC results contain duplicate conjunctions if two SDA member satellites conjunct; (2) SDA LEO member spacecraft are located in orbital regimes that do not reflect the LEO distribution as a whole.

Both trends indicate that while the number of conjunctions may have only increased by twenty percent over the past four years on a per-satellite basis, the rapid increase in the number of active LEO spacecraft has led to an almost tripling of conjunction rates in the last four years alone. This increase undoubtedly puts increased burdens on SSA systems and spacecraft operator flight dynamics personnel, raising the concern that satellite operators may not have the personnel, SSA data, and coordination in place to sufficiently guard against future collision threats.

Using the square-law from the kinetic theory of gasses, we can map the 6,000 conjunctions seen on the right side of Fig. 5 to a collision-inducing combined hard body radius of one meter, for example. In the absence of an effective collision avoidance process, this mapping indicates a collision between active LEO spacecraft and other active spacecraft or debris could occur every fourteen years.

Another aspect that Fig. 5 highlights is that of SSA data accuracy. The trend for 1 km miss distance is seeing a dramatic rise as the debris population grows, our knowledge of existing debris improves with the tracking of smaller and smaller debris, and more active spacecraft are orbited. But if we could improve our predictive positional knowledge in a substantial way, either by adopting ‘safety lanes’ or by improved tracking, data fusion and analytics [9], then the number of conjunctions flagged for follow-up due to their estimated risk could be substantially reduced, serving to counterbalance the increased resource and collision risk assessment loading.

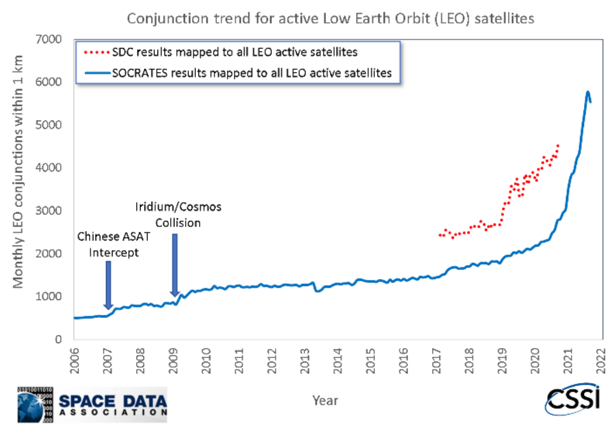
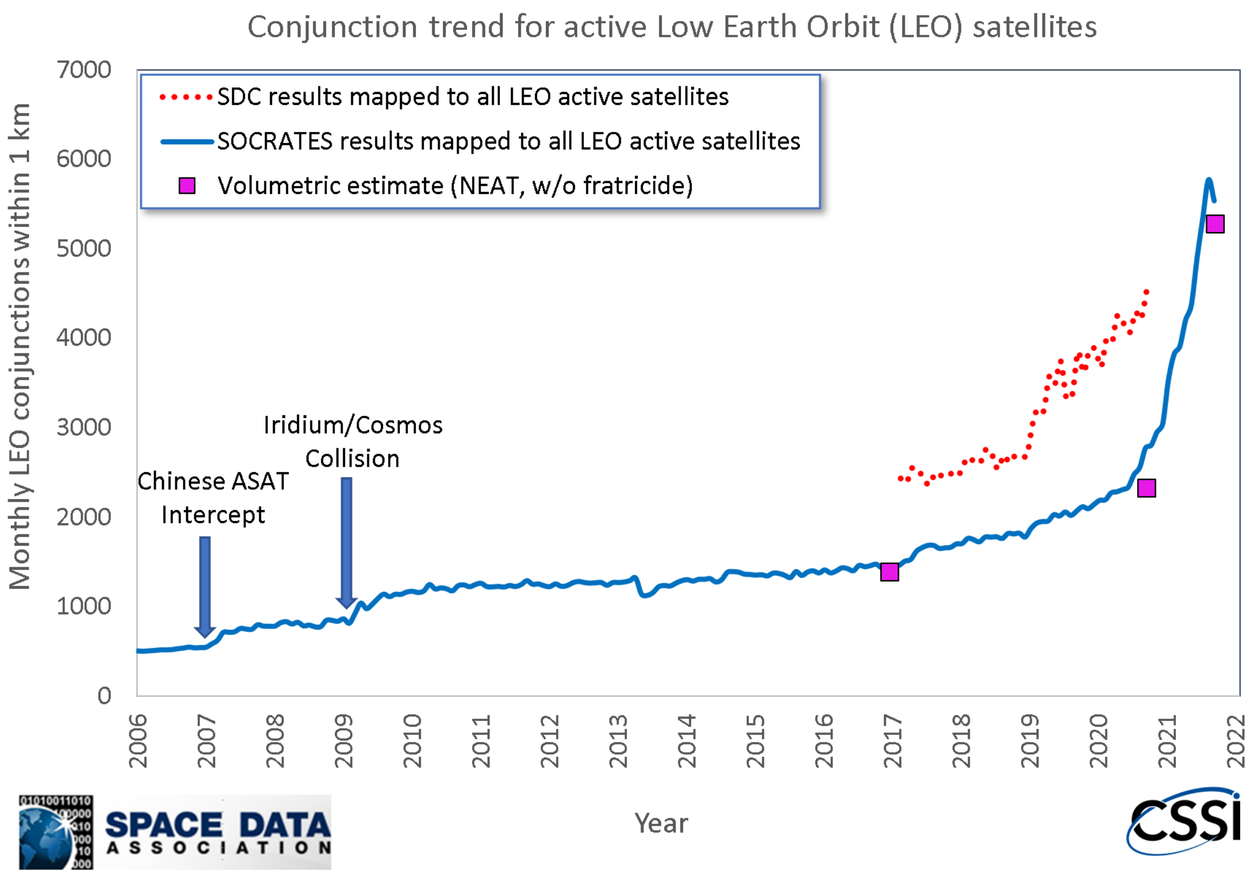


Fig. 5. SDA LEO and GEO monthly < 3 km conjunction rates

4. LEO encounter rate estimation using COMSPOC volumetric encounter rate method

The third method utilized COMSPOC’s “Probability and Frequency of Orbital Encounters” tool (U.S. Patent No 10293959), the details of which can be found in the paper “Volumetric Assessment of Satellite Encounter Rates.” [10] This tool determines average long-term encounter probability as opposed to computing near-term instantaneous collision (conjunction) probability for two satellites. Such an assessment cannot be based on in-track positions, since in-track positions of the two satellites cannot be reasonably predicted and may be assumed to be uncorrelated with each other. This approach does not attempt to find exact times of proximity and the resulting collision probability for unique close approaches. Rather, its focus is on determining the time durations and frequencies where an overlap within a prescribed ellipsoidal encounter volume could occur between two satellites randomly positioned in their orbits. It therefore determines the average aggregate number of probable encounters over a period of time to produce a reasonable expectation of proximity warnings and/or conjunctions per day. The model assumes that no effective collision avoidance process is in place to mitigate the threat of a collision. For this paper, the volumetric encounter tool was used in two different ways.

In the first application of the volumetric encounter tool, conjunctions between satellites flown by the same operator were not included in the statistics (i.e., "fratricide" was not considered). We did include conjunctions for satellites flown by different operators while also eliminating the associated double counting of such statistics. This is standard procedure for the analysis done by the Space Data Center (SDC). These results were again normalized to monthly 1 km encounter rates as done for the other methods, resulting in Fig. 6.



For the second application of the volumetric encounter rate tool, we looked at all active satellites (irrespective of their owner/operator) against the entire space catalogue (i.e., fratricide was possible and included). This is the methodology used by SOCRATES, where a list of all satellite payloads on orbit are screened against a list of all objects on orbit using the catalogue of all unclassified NORAD two-line element sets (TLEs) releasable to the public. These results were also normalized to monthly 1 km encounter rates as done for the other methods, resulting in Fig. 7.

Normally, it is a safe assumption that a single operator will safely ensure that their spacecraft cannot and will not collide with each other. But the yellow diamond in the upper right side of the plot is an indicator of just what might occur, should a large quantity of spacecraft suddenly become uncontrolled due to an unforeseen event [11] [12] [13].

In both applications, three public TLE space catalogues (dated 1 January 2017, 9 December 2020, and 15 September 2021) were assessed. The volumetric encounter tool encounter rate estimates corresponding to a 1 km standoff distance (keep out sphere radius) are summarized in Table 1.

Given that the number of fratricide conjunctions has gone from effectively zero in 2017 to a factor of 4 increase in 2021, it is worth investigating what is driving that increase. The volumetric encounter rate tool was used to examine how conjunction rates for active spacecraft against debris vary as a function of altitude as shown in Fig. 8. Note the relatively high rates (as compared to the background/vicinity rates) of conjunction at Starlink, Iridium, and OneWeb altitudes, due to the substantial increase in the number of active spacecraft present there.

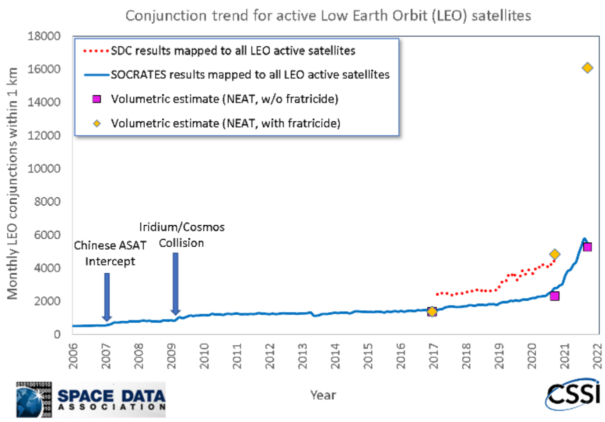


Table 1. LEO active-on-active satellite volumetric encounter rates, 2017 to 2021.

	2017	2020	2021
Active-on-Active, excluding fratricide	1,381	2,322	5,279
Active-on-Active, including fratricide	1,387	4,848	16,084

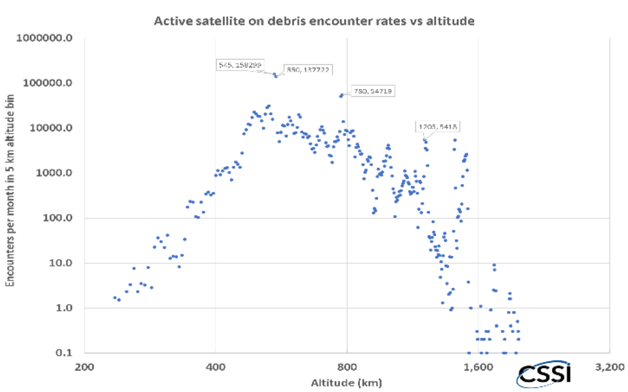


Fig. 8. Debris encounter rates as function of altitude.

A recent semi-annual report [14] filed by SpaceX indicated that they conducted 2,219 maneuvers over a six-month period, reflecting this increase in conjunction rates that warranted evasive action.

Next, we use the volumetric encounter tool to examine the rates of encounter that an active spacecraft would experience with another existing active spacecraft as shown in Fig. 9. There are two trends shown on the plot, with the lower (magenta with diamond symbols) trend corresponding to the non-fratricide case (where an operator will not allow their spacecraft to run into each other) and the upper (green with triangular symbols) corresponding to the fratricide case (where they will).

A note of caution regarding the volumetric encounter tool: The underlying algorithm assumes uncorrelated in-track motion between the two conjuncting objects, which is a legitimate assumption for spacecraft conjuncting with other debris or with other constellation spacecraft, and therefore the "excluding fratricide" magenta profile in Fig. 9 will properly reflect the expected encounter rate.

But for the "fratricide" case, this assumption of uncorrelated in-track motion is violated, because the constellations are presumably designed (certainly the case for Starlink) to avoid each other. So while the high encounter rates seen for the fratricide case at orbit altitudes of large constellations are startling, with as much as a factor of 31 localized increase in the immediate neighbourhood of the Starlink altitude at 550 km, these high encounter rates would not be realized unless the constellation (or parts of it) were to experience a loss of control and/or not be properly disposed of. It is this substantial localized increase, estimated using these failure scenario assumptions, which yields the high fratricide-based encounter rate data point on the upper right of Fig. 7.

An estimate of collision risk in the neighbourhood of large constellations which is not limited to the above assumption was provided in [15], yet it showed similar and somewhat striking increases in collision probability in the immediate vicinity of the Starlink constellation.

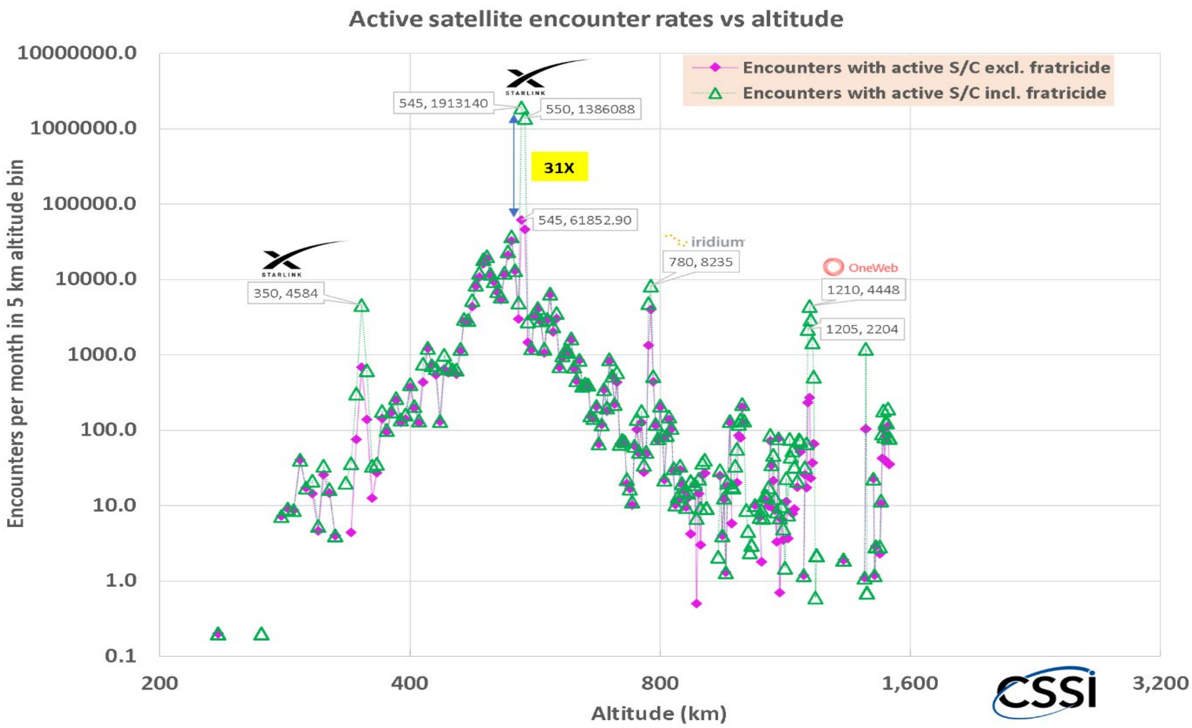


Fig. 9. Active satellite encounter rates with and without fratricide as function of altitude.

A comparison of debris-based and active encounter rate estimates is shown in Fig. 10.

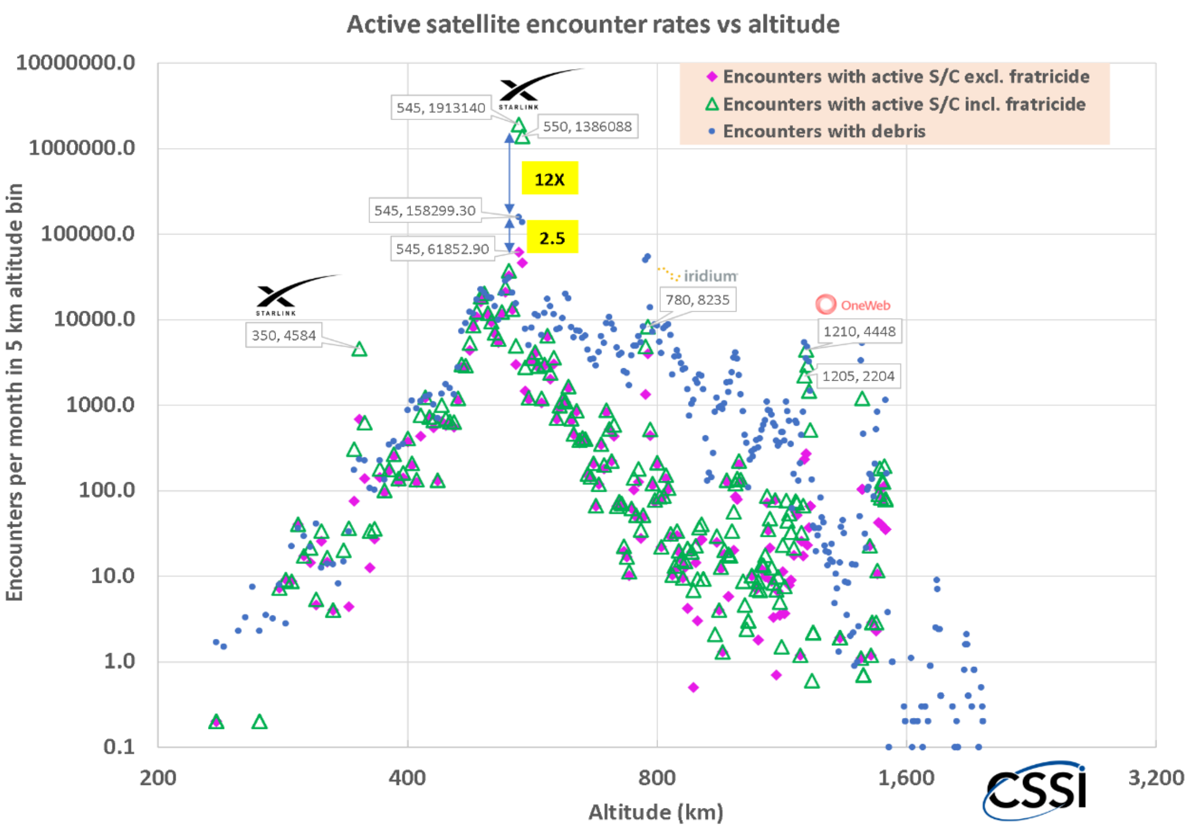


Fig. 10. Comparison of debris and active satellite encounter rates as a function of altitude.

6. Conclusions

Based upon these comparisons, we found that SOCRATES and SDC data indicate that in 2017, LEO spacecraft likely came within 1 kilometre of other objects an average of between 1,400 and 2,400 times per month. Now, just four years later, those averages are at or exceed 6,000 monthly conjunctions. This represents as much as a four-fold increase in conjunction rates.

A key takeaway from this statistical analysis of several long-standing flight safety systems is that LEO satellite operators are as a whole group receiving almost four times as many conjunction warnings as they did four years ago, and in certain localized orbit regimes and satellite operators, conjunction alerts may be increasing even faster.

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