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Space debris collision probability analysis for proposed global broadband constellations

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A B S T R A C T

Fragmentation events, caused by the collision of two objects in space, have been a significant source of space debris objects over a cumulative five decades of space activity. Current proposals by different commercial entities aim to launch constellations comprising thousands of satellites in Low Earth Orbit (LEO), which would result in an increase of more than five times the number of currently active satellites in a region where debris objects are most concentrated. The Inter-Agency Space Debris Coordination Committee (IADC) has already recognized the potential influence of large constellations on the LEO environment and the subsequent need to assess whether current mitigation guidelines will be adequate moving forward. Given developments for such constellations are already underway, independent research efforts ahead of any revision to current IADC guidelines could be of great value not only to the organizations involved in their operation, but also to policymakers and existing space users. This paper evaluates the probability of collisions for mega-constellations operating in the current LEO debris environment under best and worst-case implementation of current mitigation guidelines. Simulation studies are performed using the European Space Agency's (ESA) *MASTER-2009* debris evolutionary model, and the specifications of the proposed OneWeb and SpaceX constellations as example mega-constellations. Multiple scenarios are then tested to assess mitigation measures and their ability to minimize the probability of fragmentation events and the creation of new debris in LEO.

1. Introduction

Space debris objects pose a substantial threat to the vast network of space infrastructure upon which society is dependant for a range of services including navigation, communication, Earth observation, security and military operations. Given the number of space launches to date, the amount of space debris in orbit, and the expected number of launches planned for the near future, it is reasonable to question the ongoing sustainability of the orbital environment for space operations. The notion that a chain of collisions between debris objects (Kessler Syndrome) could result in low Earth orbit (LEO) becoming unusable, and remaining in an unusable state for perhaps thousands of years, is a concern emphasized by many researchers [e.g. Refs. [1–5]]. There have been at least 4 reported accidental hyper-velocity collision events in LEO, one of which (the collision of Iridium 33 and Cosmos 2251) contributed 2296 catalogued objects to the debris population and hundreds of thousands of un-trackable objects less than 10 cm in size [6,7]. Although the United Nation's Committee on the Peaceful Uses of Outer Space (UNCOPUOS) is the central organization tasked with the development of international debris mitigation guidelines, their policies are not legally binding. In order to be effective, their recommendations must be incorporated into rules and regulations established at a national government level. As the space economy continues to develop rapidly, it is imperative that governments ensure that regulatory policies keep pace with the expanding space capabilities within the private sector [8]. Global broadband internet delivered via Non-Geostationary Satellite Orbit (NGSO) is the next emerging capability within the commercial space sector, a service which requires constellations comprising thousands of satellites in LEO. In response to this development, recent literature has investigated the potential risk associated with operating large constellations within the space debris environment. Using simulations, researchers have considered the implications of different post-mission disposal (PMD) strategies and rates of PMD success [9], variations to constellation parameters [10], "self-induced" collision probabilities [10,11], and estimates of the number of collision avoidance manoeuvres required during operations [11]. As of writing,

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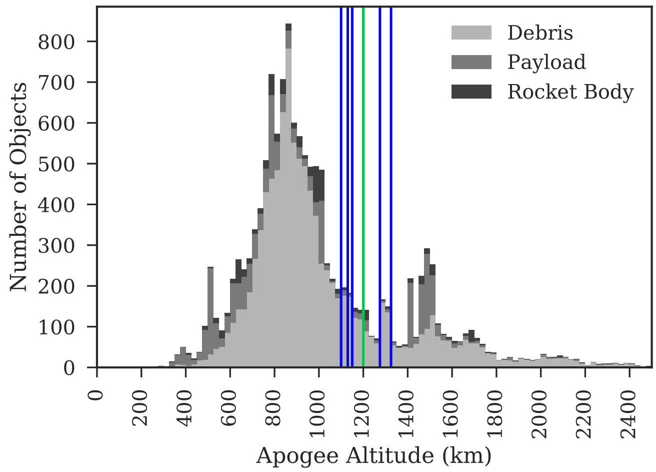

Fig. 1. Number of catalogued objects in LEO (<2500 km) with proposed operational apogee altitudes for OneWeb (green) and SpaceX (blue). Data from www.space-track.org, retrieved 4 September, 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

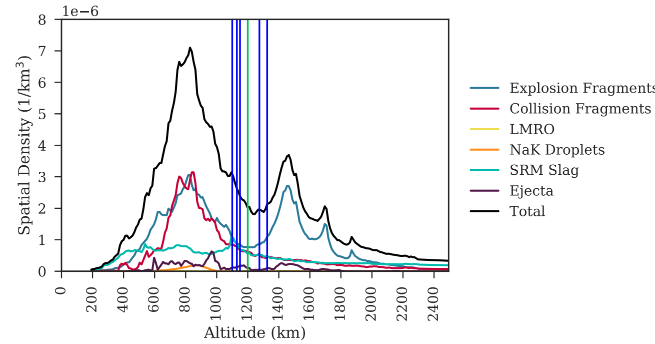

Fig. 2. MASTER-2009 output for spatial density of debris objects larger than 3 mm versus altitude for 4 September 2017.

specific policies and regulations do not exist to ensure the sustainable operation of these large constellations, yet according to licensing applications made with the Federal Communications Commission (FCC), companies such as OneWeb and SpaceX have ambitions to commence launching in the near future [12,13]. Using the SpaceX and OneWeb constellations as examples, this study uses ESA's MASTER-2009 model to evaluate the collision probability associated with large satellite constellations with future projections of the debris environment, and investigates ways in which the constellation design may be altered to reduce the probability of collision.

This paper is organized as follows. Section 2 provides an overview of NGSO constellations, including rationale for their deployment and technical parameters of the constellations used in this study. Section 3 provides a description of the methods used for the collision analysis, including an overview of ESA's MASTER-2009 model. Section 4 presents the results for collision probabilities associated with both the OneWeb and SpaceX constellations, and further analyses consider the impact of the constellation parameters and long-term impact of satellites which fail to perform a de-orbit manoeuvre. Closing remarks and topics for future research are provided in Section 5.

2. Technical parameters of NGSO constellations

Non-geostationary satellite orbit systems aim to provide low-latency, high-speed and high-capacity internet connectivity with global coverage to surpass the terrestrial equivalent in broadband internet services [14]. OneWeb, SpaceX and others have already put forward proposals to launch hundreds to thousands of satellites to provide global broadband internet services via new NGSO systems. The parameters of the OneWeb and SpaceX constellations used in this study have originated from the technical attachments provided by each of the respective operators' application to the FCC for operating authority within the United States [12,13]. Common to both applications are their proposed operational lifetime of five years, and selection of LEO altitudes. OneWeb has proposed to deploy their constellation at 1200 km while the SpaceX constellation makes use of multiple orbit altitudes on either side at 1100 km, 1130 km, 1150 km, 1275 km, and 1325 km. Fig. 1 shows the number of publicly catalogued objects in LEO, as of 4 September 2017, and the proposed operating altitudes for both constellations. It can be seen here that both operators have selected altitudes with relatively low populations of debris objects and payloads compared to other LEO regions, for example around 800 km. It is also apparent that the majority of tracked objects at these altitudes are debris, not payloads, therefore there is a greater degree of uncertainty regarding their orbits. The catalogued population is based on observational data, which typically limits the catalogue to debris objects with diameters greater than 10 cm [15]. While OneWeb and SpaceX will operate in less populated regions, the spiral up and disposal phase of their missions will pass through more densely populated regions across 800 km, and will experience an increasing debris flux. However, given that the probability of collision is highest during the operational phase, due to longer residency times [11], the analysis presented in this study focuses on the 5 year operational phase of these constellations.

Fig. 2 shows the MASTER-2009 spatial density output for 4 September 2017 obtained under the business as usual future scenario for debris objects larger than 3 mm. Here it is shown that explosion fragments, collision fragments and solid rocket motor (SRM) slag are the most significant contributors to the populations at the operational altitudes proposed by OneWeb and SpaceX.

2.1. OneWeb

On 22 June, 2017, OneWeb LLC (formerly WorldVu Satellites Limited) were granted access by the FCC to the US market using their proposed NGSO Fixed Satellite Service (FSS) system.[2] Along with other conditions documented in the *Order and Declaratory Ruling* [[16]], the FCC requires that 50% of the authorized NGSO-FSS system is launched and operational within six years of receiving authorization [17]. In December 2016, OneWeb reported their intention to launch 10 test satellites in early 2018 and, after detailed testing, the remaining 710 satellites six months later [12]. This study assumes previously reported targets by OneWeb to have their 720-satellite constellation operational from 2018 [18] which may no longer be accurate, however any delays are not expected to have a significant impact on the results presented here. Tables 1 and 2 detail the orbital and physical parameters of OneWeb's constellation satellites used for the purpose of this study.

2.2. SpaceX

The application submitted to the FCC by Space Exploration Holdings (SpaceX) proposes the launch of 4425 satellites with 166 in-orbit spares operating in 83 orbital planes [13]. Tables 3 and 4 summarize the orbital configuration and physical parameters of the SpaceX constellation satellites used for this study, as provided by SpaceX in the technical

[2] Since receiving authority for their 720-satellite NGSO-FSS system (used in the analysis presented in this paper), OneWeb has proposed to expand its constellation to 1980 satellites in a separate application to the FCC. The reader can estimate the mean number of expected collisions of the enlarged constellation by multiplying the fluence on a single satellite given in Table A.5 by the appropriate number.