SPACE DEBRIS HAZARDS FROM FRAGMENTATIONS IN COLLINEAR EARTH-MOON POINTS

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ABSTRACT

The collinear Lagrange points of the Earth-Moon system provide an ideal environment for future missions. L_1 point, which lies between the Earth and the Moon, has potential for a manned space station to transport cargo and personnel to the Moon and back. Similarly, L_2 point can be a candidate location for communication satellites covering the far side of Moon. Because, Lagrange Points promise to be the hub of future space operations, it has become important to study effect of a spacecraft fragmentation at these points. In this context, Stumpff/Weiss four-body algorithm, which is an extension of the Encke method of orbit propagation, provides a very attractive proposition for the simulation of fragment evolution. The method is 10 to 15 times faster than the other similar techniques and hence permits Monte-Carlo (MC) analysis of fragmentation velocity. Following a fragmentation at Earth-Moon collinear point about 2% of the total number of debris pieces can come within GSO altitude (~ 3.6×10^4 km). Fragmentation at any one of the Earth-Moon collinear points poses small yet perceptible risk to space operation around the Earth. It is emphasized that there is a genuine need to conduct more detailed study on fragmentation at collinear Earth-Moon points.

1. INTRODUCTION

The collinear Lagrange points of the Earth-Moon system provide an ideal environment for future missions (Figure-1). L_1 point, which lies between the Earth and the Moon, has potential for a manned space station to transport cargo and personnel to the Moon and back. In this context, it may be recalled that SMART-1 spacecraft from European Space Agency (ESA) had made a fly-by through Earth-Moon L_1 point. Similarly, L_2 point can be a candidate location for communication satellites covering the Moon's far side since orbiting about the L_2 point would allow view of both backside of the Moon and the Earth simultaneously [1]. Since, Lagrange Points promise to be the hub of future space operations, it has become important to study effect of a spacecraft fragmentation at these points. Against this backdrop, space agencies have started recognizing the need to include missions to Lagrange Points (Sun-Earth and Sun-Moon) within the ambit of space debris mitigation guidelines [2]. Accordingly, intentional breakup and accidental explosions should be prevented. Objects residing at any of the collinear Lagrange points (L_1, L_2 or L_3) are nominally unstable within the framework of Circular Restricted Three Body Problem (CR3BP) and hence velocity increments following a fragmentation event can cause migration of debris pieces to near Earth space. Earlier space debris hazards from explosions in the collinear Sun-Earth Lagrange points have been studied [3]. It is reported from the study that about half of the fragments drift towards the Earth while the other half drifts away from it. Around 2% of the simulated fragments even impact the Earth within one year after the explosion. Here for this study, a total number of 1000 fragments are generated. The velocity addition is assumed to follow isotropic distribution. The evolution of these fragments is analyzed to arrive at threat potential of a fragmentations around collinear Earth-Moon points.

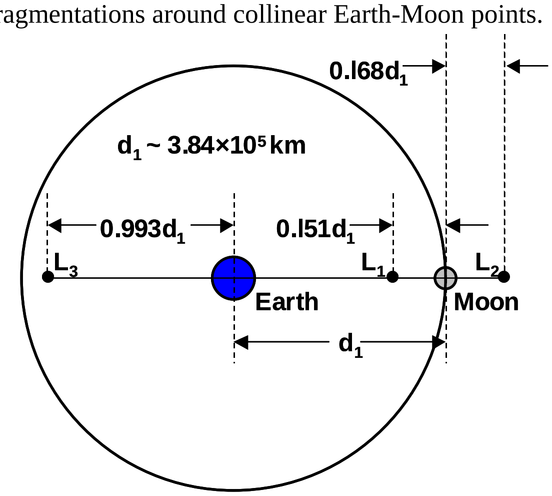

Figure-1: Schematic representation of Lagrange point locations in Earth-Moon system

2. SIMULATION METHODOLOGY

The adequacy of the force model is assessed through simulations of a typical high altitude orbit (around the Moon) for one year by considering point mass lunar

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gravity as well as by taking into account 50×50 LP150Q lunar gravity model. In both the simulations, point mass gravity perturbations of the Earth and the Sun are included. The differences in position vector are presented in Figure-2. It is observed that the maximum difference in position is of the order of 150 km. This simulation shows that it in order to simulate orbits, which are sufficiently away from the Moon; it suffices to consider only point mass lunar gravity. Since Lagrange points are more than 50000 km away from the center of the Moon, a model that utilizes only point mass gravity perturbations of the Moon, the Sun and the Earth is considered.

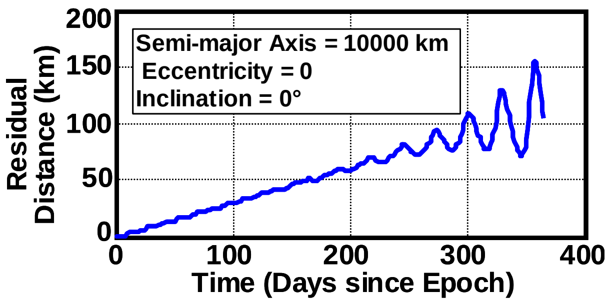

Figure-2: Typical differences in orbital evolutions (with and without full potential lunar gravity model)

In this perspective, the Stumpff/Weiss four-body algorithm [4], [5], [6] which is an extension of the Encke method of orbit propagation, provides a very attractive proposition. This algorithm determines the geocentric motion of a spacecraft in the gravitational field of the Earth, Moon and Sun from the initial conditions of each body. For these methods of solution, only the deviations between a reference orbit and the actual orbit are numerically integrated. Since the n-body perturbation between the reference and actual orbit is small, Encke methods can use larger step sizes during the integration process. The actual orbit is found by adding the integrated solution to the analytic reference orbit solution. Additionally, an important aspect of the Stumpff/Weiss algorithm is the use of an n-body reference orbit. This reference orbit has the following unique features:

(1) The reference orbit is a linear combination of Keplerian two-body orbits, which are calculated without integration.

(2) The reference orbit equations are symmetrical with respect to all planetary bodies involved in the n-body solution.

(3) The reference orbit deviates from the actual orbit by terms of the fourth order in step size.

These properties make the Stumpff/Weiss algorithm about 10 to 15 times faster than the classic Encke method. Another feature of the Stumpff/Weiss method is the fact that it does not require tabulated or analytic ephemeredes for the celestial bodies during the solution process. The position and velocity vectors of each body are computed during the solution.

Furthermore, it is still more advantageous to formulate the solution in canonical units [7]. These units consist of the correct combination of length, time and mass units such that the value of the universal gravitational constant is equal to 1. The mass of the Earth is the canonical unit of mass, and the canonical unit of length is the Earth's equatorial radius. The canonical unit of time is 806.813645 seconds.

A typical set of position and velocity vector of the Moon in Earth Centered Inertial (ECI) frame is taken as [213847.34 -296190.53 -164304.64] km and [0.84600696 0.47626001 0.17218044] km/s respectively. Similarly position and velocity vector of the Sun is taken as [-93856134 109497980 47486129] km and [-22.92052 -16.789843 -7.2817681] km/s respectively. An isotropic fragmentation of spacecraft is simulated through appropriate modification of its velocity. For this study, 1000 fragments are considered and the magnitude of incremental velocity is assumed to follow Gaussian distribution while the directions of corresponding velocity vector is generated through uniform distribution. After the breakup the pieces are propagated for one year. For each of these fragments, the average and the minimum altitude from the Earth are computed to assess the risk potential. Since, the altitude of a particular Lagrange point from the Earth is known (~ Earth-Moon altitude ~ 4×10^5 km) the migration of these fragments towards the Earth can be identified by the statistical distribution of the average and the minimum distance.

3. EARTH-MOON L_1 FRAGMENTATION

The intensities of low and high level of fragmentations are mimicked by different standard deviations for the magnitude of incremental velocity. For this study, standard deviation of 0.25 km/s and 0.50 km/s are considered. It is observed from Figure- 3 and Figure- 4 that the average altitude always remains of the order of 10^5 km or more. That about 3% of the fragments move beyond the Earth-Moon system is indicated by very high average altitude (> 10^8 km) corresponding to those fragments. But more interestingly, that about 0.1% of the fragments enters within the domain of LEO can be inferred from the minimum distance distribution. Similarly, from the same distribution, one can judge that about 1.6% of the fragments come within GSO altitude (~ 3.6×10^4 km). A fragmentation in L_1 point can pose a very small yet measurable risk to space operations around the Earth. This also emphasizes the need to conduct detailed study on breakup at collinear Earth-Moon points.

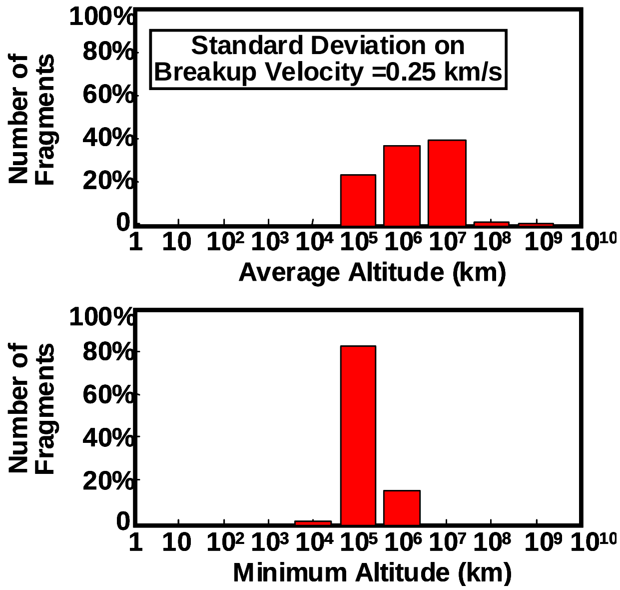

Figure-3: Distribution of average and minimum altitudes following a fragmentation at L_1 point with standard deviation on breakup velocity = 0.25 km/s

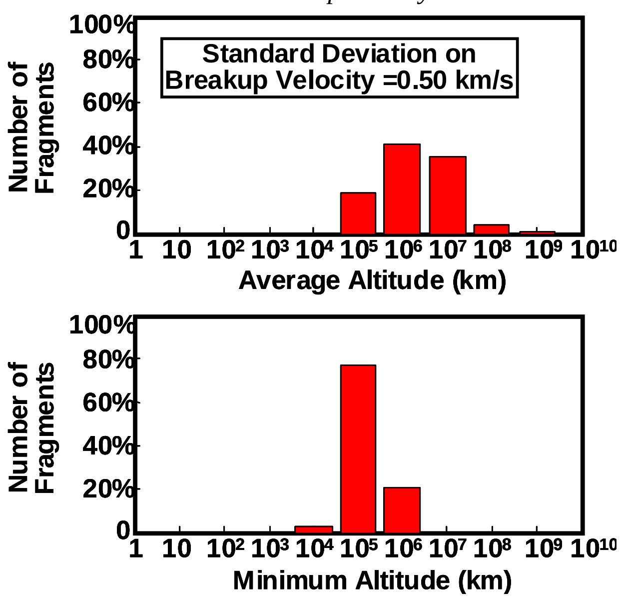

Figure-4: Distribution of average and minimum altitudes following a fragmentation at L_1 point with standard deviation on breakup velocity = 0.50 km/s

4. EARTH-MOON L_2 FRAGMENTATION

The similar study is performed for an accidental fragmentation at L_2 point. It is observed from Figure- 5 and Figure- 6 that about 2% of the fragments come within GSO altitude (~ 3.6×10^4 km). So fragmentation at any one of the Earth-Moon collinear points poses small yet perceptible risk to space operation around the Earth.

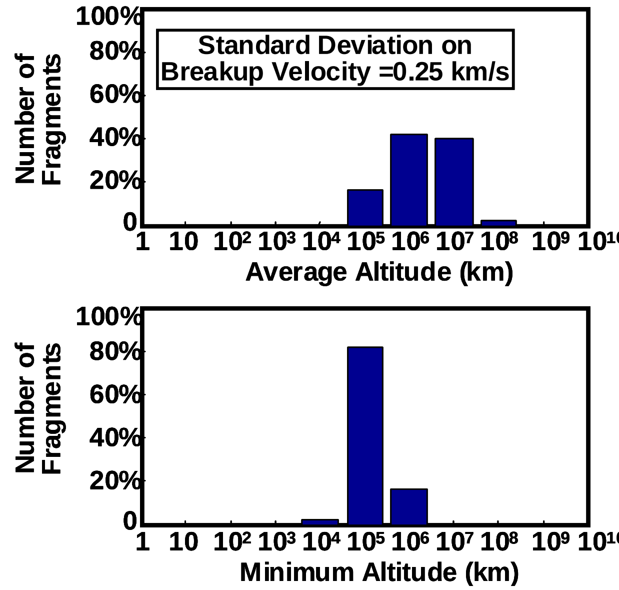

Figure-5: Distribution of average and minimum altitudes following a fragmentation at L_2 point with standard deviation on breakup velocity = 0.25 km/s

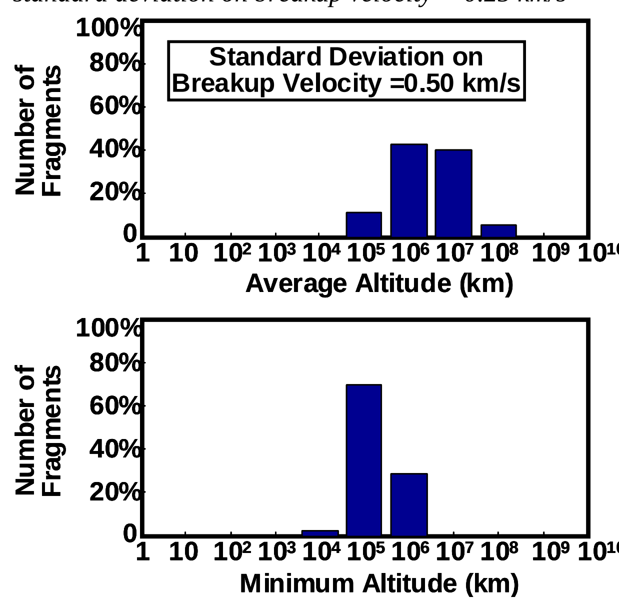

Figure-6: Distribution of average and minimum altitudes following a fragmentation at L_2 point with standard deviation on breakup velocity = 0.50 km/s

5. CONCLUSIONS

The use of the collinear Earth-Moon Lagrange points for space operations is expected to grow. Therefore, a breakup of a satellite owing to some malfunction cannot be ruled out. Following a fragmentation at Earth-Moon collinear point about 2% of the total number of debris pieces can come within GSO altitude (~ 3.6×10^4 km). So fragmentation at any one of the Earth-Moon collinear points poses small yet perceptible risk to space operation around the Earth. There is a need to conduct more detailed study on fragmentation at collinear Earth-Moon points.

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