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# An analytic method of space debris cloud evolution and its collision evaluation for constellation satellites

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**Abstract**

When a debris cloud is formed in the neighborhood of a constellation, the constellation satellites will face a serious threat of collision. In order to evaluate the collision probability in a long time scale, first we build an analytic model to describe the evolution process of the debris cloud. Under the perturbations of atmospheric drag, nonspherical gravity field, etc., results of numerical simulation indicate that after the breakup of an object, the distribution of debris cloud will evolve into a relatively stable band. Based on the stable distribution characteristic of the debris cloud, fragments are divided into several groups according their orbital heights and area-mass ratios. For each debris group, the dynamics of the distribution process under the perturbation of atmosphere drag is described by a partial differential equation (PDE). Solutions of those PDEs are obtained. And the distribution of the debris cloud can be easily propagated over long time scales. Applying this analytic model, the collision probability between a debris cloud and the Globalstar satellites is analyzed and computed. Results show that the collision probability is nearly 10,000 times of the average collision probability in the near Earth environment. Moreover, as the band distribution of the space debris cloud is stable, the collisional risk on constellation satellites will last for quite a long time.


*Keywords:* Space debris cloud; Constellation satellites; Collision probability; Analytic evolution model

## 1. Introduction

Space debris cloud consists of breakup fragments (generated by space objects' explosion or mutual collision), whose distribution is determined not only by the breakup condition but also by the complicated space perturbations including air drag force, third body force, solar radiation pressure, etc. As of June 2015, four accidental hypervelocity collisions have been recorded among cataloged debris and intact spacecraft, i.e. COSMOS 1934 spacecraft and cataloged debris 13475 (1991), CERISE spacecraft and cataloged debris 18208 (1996), THOR BURNER 2A rocket body and cataloged debris 26207 (2005), COSMOS 2251 and IRIDIUM 33 spacecraft (2009) (Pardini and Anselmo, 2014). Moreover, It has been pointed out that collisional fragments will be the most important population in the future (Liou, 2006; Wang, 2010; Yulin and Zhaokui, 2015).

Researchers found that the debris cloud originated from a breakup event would form a distribution around a sphere surface (Barrows et al., 1996; Heiner, 2006). Meanwhile, a constellation has fixed construction and steady formation. For instance, the Globalstar constellation contains 48 satellites orbiting on eight approximately circulars, six of which share one orbit. The eight orbits are at an altitude of 1414 km, and their inclinations are also kept at 52°. Therefore, all the Globalstar satellites are orbiting near a

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sphere surface with radius of 1414 km. Considering the fact that both the space debris cloud and the constellation satellites will spread around a sphere surface, the constellation satellites will face a serious threat of collision when the collision event takes place in the neighborhood of the constellation.

Building models for space debris cloud is an efficient way to study its distribution and threat to spacecraft, which contains two aspects. One is to model the collision event, so that the fragments' number and qualities (mass, cross-section area, velocity, etc.) can be determined. Usually, the NASA Standard Breakup Model (Johnson et al., 2001) is referred and adopted to simulate the breakup process. Another aspect is to build a debris cloud evolution model used to propagate the fragments' motion state, thus the collision threat to spacecraft can be evaluated over long time scales. By developing a Space Debris Impact Risk Analysis Tool (SDIRAT) and using a realistic space debris population, the instant space debris impact risk on a given target in orbit was assessed (Pardini and Anselmo, 1999). SDIRAT has been utilized to evaluate the impact flux of cataloged objects on two operational constellations, i.e. Iridium and COSMO-SkyMed (Pardini and Anselmo, 2013). Results shown that, with three debris clouds formed from catastrophic collisional breakups of Cosmos 2251 and Iridium 33 and Fengyun 1C, the flux increased with respect to the debris background was 160% at 1 May 2011, on average, for the Iridium satellites. However, the long-term effect of debris cloud on constellation satellites hasn't been analyzed. Using the Space Debris Simulation (SDS) software, it was found that the probability of exiting debris impact to the constellation was low, but a collision-induced breakup of a constellation satellite posed the greatest risk to the remainder of the constellation (Swinerd et al., 1999). The SDS was only suited for short- to medium-term analysis (hours to months after the initial breakup), thus the long-term effect was not addressed. Recently, a three-dimensional LEO-to-GEO debris evolutionary model (LEGEND) was developed by Liou et al. (2004) to study the space debris evolution, which was a computing model and has been applied to analyze the characteristic of debris cloud consisted of an on-orbit breakup fragments (Liou and Johnson, 2009). The fragments' size and area-mass ratio (A/M) distributions were carefully analyzed and their long-term impact to the LEO debris environment was simulated. Space debris evolution model, like LEGEND, SDS or the Space Debris Mitigation long-term analysis program (SDM) (Rossi et al., 2009), which takes each of the fragments as a propagation object, will make the model time-consuming while the accuracy of the result is unknown (Nazarenko, 2014).

Meanwhile, Talent has developed a deterministic analysis model to study the space debris (Talent, 1992), while Kessler (1991), (2002), Smirnov (2002) and Rossi et al. (1998) built stochastic models. After deriving a set of partial differential equations, McInnes studied the evolution of the mean spatial number density of the constellation under the action of air drag, on-orbit satellite failures, and the deposition of new satellites into the constellation (McInnes, 2000), which is worth using for reference when study the long term evolution of space debris cloud. By taking the number of the space debris as a state variable or by dividing space debris into several groups, those models can be used to propagate the number or the representative state of a group of the debris, which made the motion propagation less time-consuming. For instance, reference (Letizia et al., 2015) utilized an analytical model to propagate the small-sized fragments, which reduced the computational time of space debris cloud long-term evolution under 10% compared to the numerical propagation of all fragments.

In the present work, based on the method analyzed in references (McInnes, 2000) and (Letizia et al., 2015), an analytical method is proposed to study the evolution of space debris cloud. Firstly, the distribution characteristic of space debris cloud is analyzed numerically. Based on the numerical result, the debris cloud is divided into several groups according their orbital heights and area-mass ratios. Then, for each debris group, the dynamics of the distribution process of the debris cloud under the perturbation of air drag is described by partial differential equation. And in each group, different parameters of atmosphere density have been chosen. Finally, with the analytic evolution model, the distribution state of the space debris cloud could be easily propagated. As an application case, the analytic model is applied to analyze the distribution state of a debris cloud and its collision probability on Globalstar satellites over a long time scale.

## 2. Space debris cloud distribution characteristic analysis using numerical method

A great number of fragments will be produced after an on-orbit breakup event caused by space objects' self-explosions or mutual collisions. Under the effect of the Earth's gravity force and perturbations, like air drag force, third body force, etc., fragments will evolve into a cloud of debris. In order to evaluate the collision probability between the debris cloud and the constellation satellites, the distribution characteristic of the debris cloud is analyzed in this section.

The process and the outcome of an on-orbit object breakup is quite complicated, it is not only associated with the motion state of the object, but also affected by the structure and material of object. The NASA Standard Breakup Model (Johnson et al., 2001; Krisko, 2011) is introduced here to produce the breakup fragments. Then the debris cloud is numerically evolved using a space object motion propagation system, and the distribution characteristic is finally analyzed.

### 2.1. The breakup model and its numerical implementation

The NASA Standard Breakup Model is briefly introduced here for clarity. Taking the characteristic length $l$