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ANALYSIS OF CLOSE APPROACHES BETWEEN SMALL SATELLITES AND CATALOG OBJECTS

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Small satellites have been widely applied in communication, remote sensing, astronomy, experiments and many other aspects of space activities. It can be anticipated that a large number of Ultra Low Mass (ULM) satellites (<15kg) will be launched to space in the next few decades, and these will become a potential source of orbital debris for lack of de-orbit capabilities. In this paper, the orbital distribution of current ULM satellites was investigated, which showed that all ULM satellites are in Low Earth Orbit (LEO) and most of them locate in Sun Synchronous Orbits (SSO) within the altitude band 600-900Km. The close approaches between all objects in the satellite catalog and ULM satellites against the satellite catalog were calculated based on data from the US Space Surveillance Network (SSN), which was taken as the baseline for comparison. Close approaches for different growth models of ULM satellites in their often used altitude band were tested, and the resulting collision probabilities were compared with the baseline scenario. The simulations were based on a conjunction algorithm and related collision rate estimation method presented by Wang Ting. The results of this study indicate that (1) the orbit concentration of future ULM satellites will have a large effect on the debris environment, and (2) the number of future ULM satellites which will be sent to heavily used SSO LEO altitudes should be regulated to reduce the collision risk to larger satellites.

I. INTRODUCTION

Recent advances in technology have made it possible to miniaturize many satellite components, and in turn reduce the size of functional satellite dramatically. Compared to historical satellites that are on the order of 1000 kg, micro-satellites typically weigh between 10 kg and 100 kg, nano-satellites are typically less than 10 kg, and pico-satellites are less than 1 kg. These classes of satellites are becoming increasingly popular for universities and other entities because of their small size, mass and low manufacturing and launch costs.

In the past ten years, nearly 70 Ultra Low Mass (ULM) satellites (<15Kg) have been sent to orbit, most of which were deployed in Low Earth Orbit (LEO, defined as the region between altitudes of 200 and 2,000 km) (Brian, 2010). It can be anticipated that much more this level small satellites will be sent to space in the next few decades. Since ULM satellites are smaller in size and lower in mass than traditional satellites, they are difficult to track with existing space situational awareness capabilities and may not have de-orbit or maneuver capability. Therefore, it is unlikely that they can be moved to 25-year decay orbits or to LEO storage orbits (above 2,000km altitude) at the end of mission lifetimes, in accordance with existing space debris mitigation guidelines, which makes them a potential source of orbital debris.

In cases with a high relative speed, collisions with debris larger than 10cm can seriously damage or destroy a satellite, which will then create large amount of fragments. The additional particles further increase the collision probability in the region, which leads a slow-motion chain reaction that could make some orbital regions unstable. The situation is called the Kessler syndrome predicted by Kessler and Cour-Palais (Kessler and Cour-Palais 1978, 2637–2646; Kessler 1991, 63–66). The 2009 collision of the Iridium 33 and the Cosmos 2251 signaled a beginning of this trend (Ting W. 2010, 87-118). To better preserve the near-Earth environment for future space generations, remediation measures, such as space traffic management (COSMIC 2006) and active debris removal (J.-C. Liou 2008, 236-243), have been considered besides space debris mitigation guidelines by United Nations and national space agencies (NASA Orbital Program Office 2007, 1). Space traffic management concepts have been presented and studied in the last decade which showed that conjunction assessment should be indispensable technical basis for collision risk estimation and collision warning (Johnson 2004, 803-809; ISU 2007; Haydar and Ilker 2009, 870-878). With the growth in the number of small satellites, the close approaches and collision rate resulting from the increasing numbers of small satellites should be estimated, which could provide technical basis for potential small satellite traffic management solutions.

In this paper, the spatial distribution of current ULM satellites was investigated first; then the future impact of ULM population growth was assessed by evaluating close approaches between a ULM population of 100 to 1,000 satellites and SSN (US Space Surveillance Network) catalogued; finally, the collision probabilities for this future scenario were estimated based on the results of conjunction assessment.

II. SPATIAL DISTRIBUTION OF CURRENT ULM SATELLITES

For low launch costs, ULM satellites are often launched as secondary payloads along with much larger satellites. This means they are concentrated in those regions that are heavily used by larger satellites. As of May 1, 2011, there were 965 operational satellites in orbit around the earth, according to open source estimates (UCS satellites database). Included in this number are 38 ULM satellites, which are all deployed in LEO and most of them are in Sun Synchronous Orbits (SSO). The inclination and altitude distribution of ULM satellites is shown in Fig.1 (Brian, 2010).

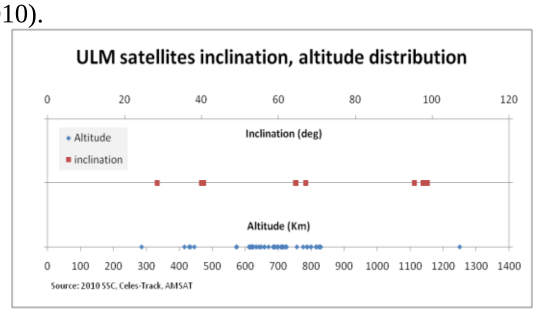

Fig.1: ULM satellites inclination, altitude distribution

It can be seen that ULM satellites are concentrated in altitude band from 600 to 900km, and the inclination of SSO within this range altitude is about 98 deg. These orbital parameters indicate that these satellite are generally used for earth observation. At these altitudes, ULM satellites could remain in orbit for decades or even hundreds of years, depending on their area-to-mass ratio. ULM satellites with lower orbital altitude (200-600Km) will fall into atmosphere in a much shorter period and thus they pose much less of a collision concern.

Based on the preceding orbital distribution of current ULM satellites, the authors assume that the future growth of the ULM satellite population will be in the SSO region for the purpose of the remaining analyses in this paper.

III. CLOSE APPROACHES ANALYSIS

A. Modeling tool

The problem of calculation close approaches events among space objects can be expressed as, at a given time span [t_B, t_E], whether two objects are within some specified critical distance *D*. If they are, the minimal distance and time of close approach is required to be calculated.

A conjunction detection algorithm called numerical-geometrical method is applied in the present calculation, which was presented by Wang Ting in 2007 (Ting W 2008). It could be applied to calculate conjunctions of the complete catalog against itself and also of a spacecraft against the catalog.

The close approach calculation involves four parts: altitude filter, geometry filter, ‘smart sieve’ and relative distance function. During the calculation, we pick an object from the catalog (named as target) and detect the conjunctions of the target against every object in the catalog (named as risk object). Remove the target from the catalog after the detections. Repeat this process until all objects are removed. The methods are proved to be effective, and ensure finding all conjunctions.

B. Conjunctions of current debris environment

We calculated conjunctions of current SSN catalog against itself (Case 1) and operational ULM satellites against the catalog (Case 2) from 0:00, July 7, 2011 to 0:00, July 8, 2011, based on unclassified historical NORAD TLEs, which have more than 14000 space objects. In that time span, when taking 5 km as critical distance *D*, there are 10,514 conjunctions in Case 1, where more than 99.9 % of conjunctions (10,513) are in LEO, indicating this is the area of most concern.

Fig.2 illustrates the conjunctions for these two cases as a function of critical distance *D*. We find that linear increase in the critical distance leads to quadratic increase in cumulative sum of conjunctions in both cases. Based on this characteristic, we can estimate conjunction number of one critical distance D_0 from that of another critical distance D_1:

$$N_0 = (\frac{D_0}{D_1})^2 N_1 \qquad [1]$$

where N_0 is the conjunction number corresponding to D_0, N_1 is the conjunction number corresponding to D_1. Therefore, for instance, we can estimate that the conjunction number of critical distance 20*Km* is 168,224 during the same period. This characteristic is helpful for us to estimate the collision probability.

Fig.2 also shows that the conjunctions induced by the operational ULM satellites are a very small percentage of the overall conjunctions form all objects in LEO. The next fundamental question is how this situation changes with a future increase in the ULM population in this region.

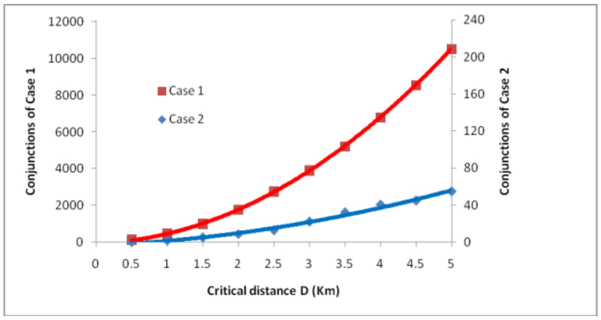

Fig.2 Cumulative distribution of conjunctions as function of critical distance

C. ULM satellite population growth scenarios

To examine future scenarios with larger ULM satellite populations, we assumed that there will be a rapid growth of ULM satellites in LEO. Varying numbers of ULM satellites are deployed into LEO, which are all in SSO with zero eccentricity. The altitudes of them range between 600km and 900km. The right ascension of the ascending node, argument of perigee and mean motion are randomly generated.

Using the SSN catalog of July 7, 2011, we calculated conjunctions of updated databases against themselves during one day, with the increment of ULM satellites from 100 to 1000. Each scenario included 100 runs.

Fig.3 showed the conjunctions detected when D is 5km. It illustrated that conjunctions of updated databases against themselves are increasing linearly with respect to the growth of ULM satellites. The increased conjunctions are also shown in Fig.3. We can see that the conjunction number will increase 2712 compared with Case 1 if we put additional 1000 ULM satellites into SSO, which accounts for 25.8% of conjunctions in present LEO environment. Since no future launches are considered in the catalog, the real situation will even worse than the present results.

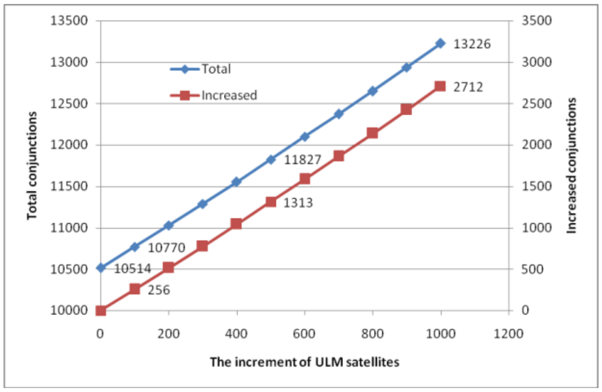

Fig.3 : Conjunction numbers with growth of ULM satellites

The distribution of conjunctions as a function of altitude is shown in Fig.4. It showed that conjunction numbers increased mainly in altitude band of 600-900*Km*, with only minimal impacts on other altitude bands. This indicates that the negative impact of large numbers of ULM satellites could be reduced if the number of these satellites deployed in the SSO orbital region were minimized. For instance, if the future ULM satellites are all deployed in altitude lower than 600*Km*, then, the conjunction will increase much slower than that in 600-900*Km*, as shown in Fig.5. In addition, objects run in orbit altitude lower than 600km usually can decay in short period of time, and thus will not have a long term impact on the space debris environment.

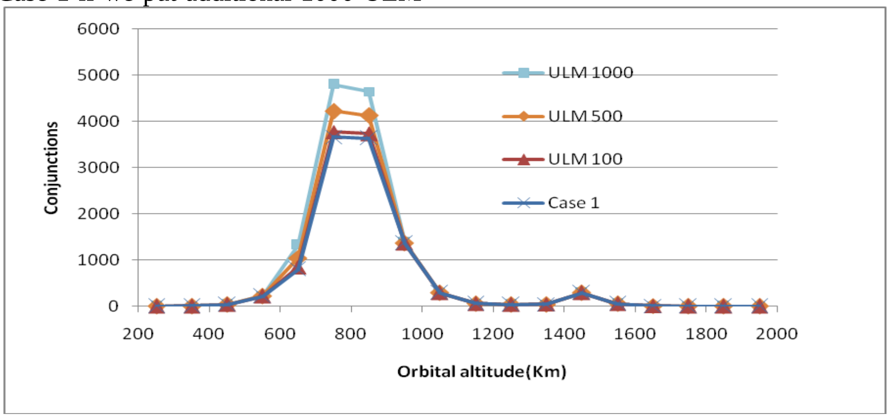

Fig.4: Comparison of altitude distributions of four different scenarios. From top to bottom: 1000 ULM satellites growth, 500 ULM satellites growth, 100 ULM satellites growth, case 1.

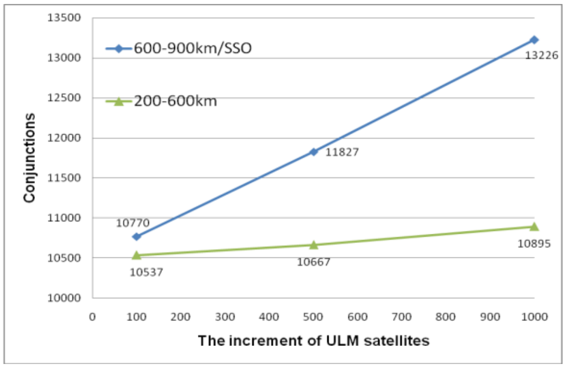

Fig.5: Comparison of ULM satellites growth in different altitude bands

IV. COLLISION PROBABILITY ESTIMATION

A. Estimation method

Based on the conjunctions and related characteristic obtained in section III, a method established by Wang Ting (Ting W 2009) was applied to calculate collision probability of all catalogued objects in LEO.

The method is based on two assumptions:

(1) Collision flux (*f*, is defined as conjunction number when *D* is 1*m* and time span of interest is one year) around each object is same;

(2) An object will only be impacted by objects that among close approaches.

According to Eq.1, the mean collision number of all LEO catalogued objects c_{LEO} can be expressed by

$$c_{LEO} = f_{LEO} D_{mean} t \quad [2]$$

Where f_{LEO} is collision flux of all LEO catalogued objects, $f_{LEO} = N_{D,LEO,\Delta t} / (\pi D^2 \Delta t)$, $N_{D,LEO,\Delta t}$ is conjunction number with critical distance *D* during time step length Δt. S_{mean} is equivalent cross-sectional area, $S_{mean} = \pi d_{mean}^2$. d_{mean} is mean distance of all LEO catalogued objects, which could be obtained with the follow equation,

$$d_{mean} = \sqrt{\frac{\sum_{k=1}^{K} (r_i + r_j)^2}{K}} \quad [3]$$

Where r_i, r_j are equivalent radius (length + width + height / 3) of the *i*-th and *j*-th orbital objects, respectively. For SSN catalogued objects, the equivalent radius could be transformed from the published radar cross-sectional area RCS (Ting W 2009). *K* is the conjunction number.

After the d_{mean} is obtained, the collision number c_{LEO} could be calculated. Then, the collision probability between catalogued objects could be achieved according to probability theory.

B. Simulation results

In the collision probability calculations, we assumed that the equivalent radius of ULM satellites is 0.3*m*. No explosions and breakups were allowed for rocket bodies and payloads, and even no other launches beside ULM satellites.

Fig.6 showed that the collision probability with the growth of ULM satellites, altitude distribution of which were same as that assumed in section III. It illustrates that collision probabilities are increasing linearly with respect to the growth of ULM satellites. That is, if 100 ULM satellites were sent to heavily used LEO orbit band, the collision probability would increase 1.1% from 0.282 to 0.285; and if 1000 ULM satellites growth, collision probability would increase 11%. Although it seems that this is a relatively small increase, in reality, the situation will be worse than this “no other launches and no future breakups” scenario, since larger satellite launches will continue to occur and breakup events will happen once per three years according to the present results.

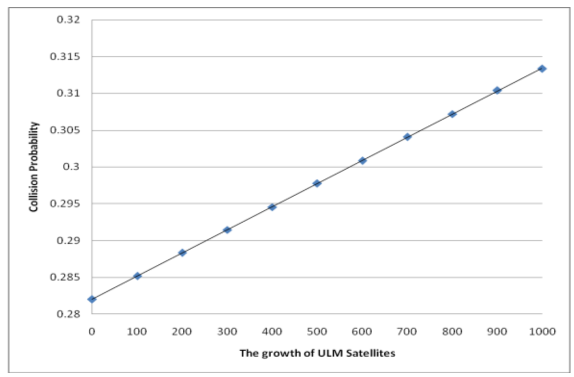

Fig. 6: Collision probabilities with growth of ULM satellites

VII. CONLUSIONS

It can be concluded from the orbital analysis of ULM satellites and simulation results as follow:

(1) All current ULM satellites in orbit are deployed in LEO, and most of them are in Sun Synchronous Orbits (SSO), which are concentrated in altitude band from 600 to 900km.

(2) The increase in close approaches between the existing catalog and further ULM satellites populations is closely related with orbital altitude. It could be suggested to ULM satellites designers to avoiding 600~900Km orbit altitude, especially 700~900 Km.

(3) The collision probability will increase more than 10% if 1000 ULM satellites were deployed to heavily used LEO orbital altitude. It means that the number of future ULM satellites which orbits are designed as heavily

used orbital band should be controlled to an appropriate level so as to suppression the collision probability.

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References:

Brian W. 2010. “Small satellite traffic management.” 2010 Beijing Orbital Debris Workshop, Oct 18-19, Beijing. Available at http://swfound.org/media/28359/Weeden-SmallsatSTM.pdf

C. Contant-Jorgenson, P. Lala, and K. U. Schrogl (eds.) (COSMIC) 2006. “Cosmic Study on Space Traffic Management.” International Academy of Astronautics, France.

Cukurtepe, Haydar and Akgun, Ilker. 2009. “Towards space traffic management system.” Acta Astronautica, vol. 65, pp. 870-878.

Inter-Agency Space Debris Coordination Committee (IADC). 2002. IADC Space Debris Mitigation Guidelines. Available at http://www.iadc-online.org/index.cgi?item=docs_pub

ISU Student Report. 2007. “Space traffic management final report.” International Space University Summer Session Program, China, available at http://www.isunet.edu/index.php/sturep-ssp

J.-C. Liou, N. L. Johnson. 2008. “A sensitivity study of the effectiveness of active debris removal in LEO.” Acta Astronautica, vol.64, pp. 236-243.

Kessler, D.J., Cour-Palais, B.G. 1978. “Collision frequency of artificial satellites: The creation of a debris belt.” JGR, vol.83, no.A6, pp. 2637–2646.

Kessler, D.J. 1991. “Collisional cascading: The limits of population growth in low Earth orbit. “Advances in Space Research, vol.11, no.12, pp.63–66.

NASA Orbital Program Office. 2007. Orbital Debris Quarterly News, vol.11, no.2, pp.1, available at http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv11i2.pdf

N.L. Johnson. 2004. “Space traffic management: concepts and practices.” Acta Astronautics, vol.55, pp.803-809.

Satellite database of Union of Concerned Scientists. Available at http://www.ucsusa.org/nuclear_weapons_and_global_security/space_weapons/technical_issues/ucs-satellite-database.html

Ting W, Huang H. 2008. “New Method to Determine Close Approaches Between Satellite.” Proceeding of 3rd IAASS Conference, Rome. Available at http://wangting.org/pages/papers/close%20approach.pdf

Ting W. 2009. Orbital Debris Evolution and Threat to Spacecraft. Doctoral degree thesis. Beihang University. (in Chinese)

Ting W. 2010. “Analysis of debris from collision of Cosmos 2251 and the Iridium 33 satellites.” Science & Global Security, vol 18, pp.87-118.