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Procedia Engineering 67 (2013) 404 – 411
Procedia Engineering
www.elsevier.com/locate/procedia

7th Asian-Pacific Conference on Aerospace Technology and Science, 7th APCATS 2013

Orbital Debris Modeling and Applications at Kyushu University

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Abstract

The orbital debris modeling can build evolutionary models as essential tools to predict the current or future orbital debris populations, and also to discuss what and how to do for orbital debris mitigation and environmental remediation. The orbital debris modeling can also devise an effective search strategy applicable for breakup fragments in the geostationary region using ground-based optical sensors, and to evaluate the effectiveness of space-based measurements of objects not tracked from the ground, both to contribute to space situational awareness. Another application of the orbital debris modeling is to estimate attitude motion of space objects to be removed for environmental remediation. This paper briefly introduces efforts into orbital debris modeling and applications at Kyushu University.

Selection and peer-review under responsibility of the National Chiao Tung University

Keywords: Space environment, Orbital debris, Orbit propagation.

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1. Introduction

Orbital debris modeling mainly consists of debris generation and orbit propagation. Thus, orbital debris modeling at Kyushu University was initiated with satellite impact testing to understand debris generation. Debris generation can characterize and predict physical properties of fragments originating from explosions or collisions. After completion of the initial study of satellite impact testing, Kyushu University started to develop an orbital debris evolutionary model. The evolutionary model is an essential tool to predict the current or future orbital debris populations, and to discuss what and how to do for orbital debris mitigation and environmental remediation.

Since the evolutionary model requires an orbit propagator, Kyushu University also started to develop it. Orbit propagation can characterize, track, and predict the behavior of individual or groups of space objects. With debris generation, therefore, orbit propagation can devise an effective search strategy applicable for breakup fragments in the geostationary region using ground-based optical sensors, and to evaluate the effectiveness of space-based measurements of objects not tracked from the ground, both to contribute to space situational awareness.

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Selection and peer-review under responsibility of the National Chiao Tung University
doi:10.1016/j.proeng.2013.12.040

Another application of the orbital debris modeling is to estimate attitude motion of space objects to be removed for environmental remediation. The attitude motion can be estimated through light curve, the change of light intensity in optical measurements. Light curve of an object can be described mathematically by taking into account shape of the object, attitude and orbit motions of the object, and geometrical relationships between the Sun, the object, and an observer. Once the light curve can be described mathematically, one may be able to estimate adequately the attitude motion through light curves.

This paper briefly introduces efforts into orbital debris modeling and applications at Kyushu University.

2. Debris Generation

Orbital debris modeling at Kyushu University was initiated with satellite impact testing to understand debris generation. First, as an initial study, simulated spacecraft walls were selected as targets, and the outcomes were all non-catastrophic (only a small amount of fragments were generated from impact craters or holes on the target walls [1]). Second, CANSAT, a micro-satellite popularized in universities teaching space engineering, was prepared to investigate the outcome of a catastrophic impact [2]. Third, 15-cm cubic micro-satellites were prepared to investigate the outcome of hypervelocity and low-velocity impacts [3]. Fourth, 20-cm cubic micro-satellites were prepared to investigate the effects of impact directions [4]. Finally, 20-cm cubic micro-satellites covered with multi-layer insulation (MLI) and equipped with a solar panel were prepared to investigate MLI and solar panel pieces [5].

Fragments down to approximately 2 mm in size were analysed based on the NASA standard break model 2001 revision [6]. The NASA standard breakup model consists of: 1) size distribution to specify the number of fragments for a given size and larger, 2) area-to-mass ratio distribution to specify a possible value for a given size, 3) size-to-area conversion to obtain mass from a given area-to-mass ratio, and 4) delta velocity distribution to specify a possible value for a given area-to-mass ratio. One of interesting results can be found in Fig 1, which compares the area-to-mass ratio distribution of fragments observed from the last satellite impact testing with the NASA standard breakup model. The NASA standard breakup model has just one peak, whereas the measured area-to-mass ratio distributions have two major peaks, corresponding to high- and low-density materials. The former includes metals, whereas the latter includes plastics. Two more minor peaks, which MLI pieces form, can be also observed in Fig. 1.

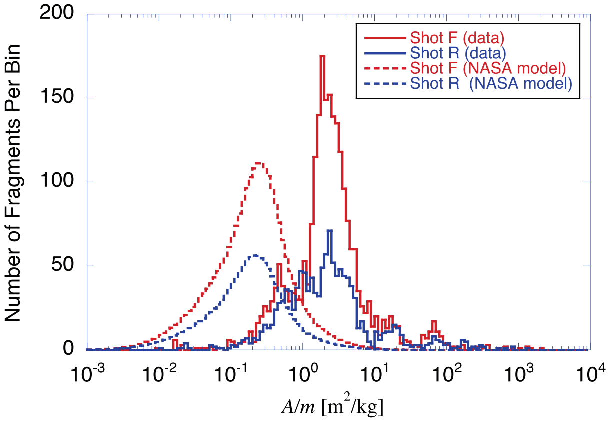

Fig. 1. Area-to-mass ratio distribution from fragments observed from impact testing using 20-cm cubic micro-satellites covered with MLI and equipped with a solar panel.

3. Orbit Propagation

Research and development on orbit propagation was also initiated after completion of the initial study of satellite impact testing. First, two different numerical orbit integrators have been developed, which can reproduce archived orbital history of selected objects. One integrates the rate of change of the classical orbital elements in the Gaussian form of the variation of parameter equations [7], whereas another is based on the Cowell's formulation [8]. Second, an analytical orbit integrator to be used in orbital debris evolutionary models has been developed, which calculates only the secular and long-term variations of the classical orbital elements. In addition to the spherically symmetric gravitational force of the Earth, a number of perturbing accelerations affect the orbit of an Earth-orbiting object. The orbit propagators include: 1) the non-spherical part of the Earth's gravitational force, 2) atmospheric drag, 3) gravitational attractions due to the Sun and Moon, and 4) solar radiation pressure.

Combination of orbit propagation with debris generation can characterize, track, and predict the behavior of groups of fragmentation debris [9,10]. Fig. 2 demonstrates orbital evolution of fragmentation debris from the known US Titan IIIC Transtage explosion in February 1992. Filled circles represent the 1-year-interval orbital evolution of the US Titan IIIC Transtage. Fragmentation debris formed a straight line at the explosion, then the line is getting deformed over time, but fragmentation debris still maintain distinctive patterns centering on the US Titan IIIC Transtage.

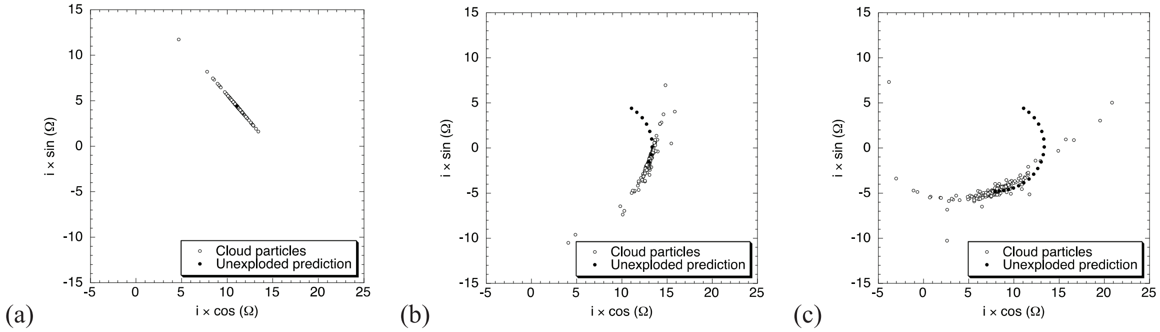

Fig. 2. Orbital evolution of US Titan IIIC Transtage fragments: (a) 21 February 1992, (b) 1 January 2000, and (c) 1 January 2010.

4. Evolutionary Models

Combination of debris generation and orbit propagation can build orbital debris evolutionary models as essential tools to predict the future orbital debris population, and also to discuss what and how to do for orbital debris mitigation and environmental remediation. First, Kyushu University developed an orbital debris evolutionary model for the geostationary region, named GEODEEM [11-14]. The GEODEEM tracks all objects which meet the following criteria: 1) eccentricity smaller than 0.2, 2) mean motion between 0.9 and 1.1 revolution per day, and 3) inclination lower than 30 degrees. Second, Kyushu University developed an orbital debris evolutionary model for the low Earth orbit region, named LEODEEM, jointly with Japan Aerospace Exploration Agency [15,16]. The LEODEEM tracks all objects with perigee altitudes below 2000 km. Finally, both models have been merged into a new orbital debris evolutionary model, named NEODEEM, to track all Earth-orbiting objects. Now, future projections are being conducted by NEODEEM.

One of interesting results from future projections is that the current debris population in the low Earth orbit region would continue to increase even with an ideal best-case scenario (no new launches and future explosions). As demonstrated in Fig. 3, intact and mission-related objects in red, and explosion fragments in green decrease over time due to the atmospheric drag. Thus, the total number in black also decreases. This is true but only at the beginning of the projection. The total number increases as collision fragments are newly generated. This result indicates that the volume of debris in the low Earth orbit region is so high that objects in orbit are frequently struck by debris, creating more debris and a greater risk of further impacts.

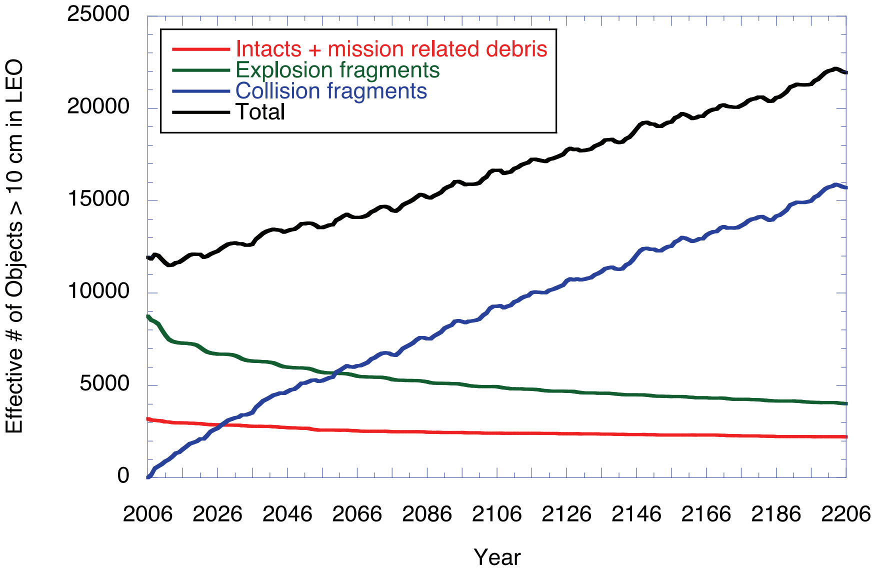

Fig. 3. Population growth in the low Earth orbit region with altitudes below 2000 km.

5. Light Curve

As demonstrated in Fig. 3, the current debris population in the low Earth orbit region would continue to increase even without new launches and future explosions. Therefore, orbital debris removal is believed to be essential for sustainable space development and utilization for humankind. It may be difficult for any orbital debris removal systems to approach and catch or grasp tumbling objects, however. Thus, knowledge on how objects to be removed are tumbling may be required in terms of orbital debris removal. Such attitude motion can be estimated through light curve, the change of brightness of objects in optical measurements. Currently, Kyushu University is developing a simulation code to understand dynamics of light curves under full orbit perturbations, and applying light curve inversion techniques, often used for asteroid, to orbital debris to estimate their attitude motion [17,18].

Fig. 4 demonstrates light curves of a rocket body with a mass of 3.0 metric ton, a radius of 2.0 m, and a length of 9.2 m. Broken line represents a light curve under no perturbation, whereas solid lines represent light curves under various orbit perturbations and external torques. It is known that several paths are required for the light curve inversion technique because various geometrical conditions between the Sun and the observer help to estimate the object's attitude using a optimization method such as least squares solution. However, the light curves get delayed by considering full perturbations and external torques as demonstrated in Fig. 4, and this time delay may cause a large modeling error of the light curve, and may not be able to properly estimate attitude motion. Therefore, Kyushu University is working on attitude motion estimation by modeling light curves properly.

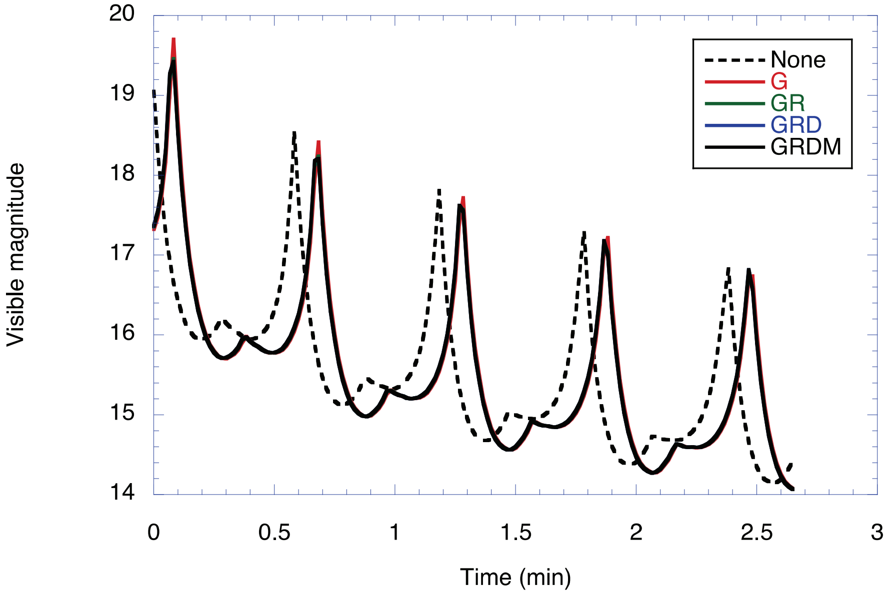

Fig. 4. Light curves of a rocket body under various external torques (G, R, D, and M represent gravitational, solar radiation, aerodynamic, and magnetic torques, respectively).

6. Optical Measurements

As demonstrated in Fig. 2, combination of orbit propagation with debris generation can characterize, track, and predict the behavior of groups of fragmentation debris. Such predictive analyses can devise a practical method for debris measurements. First, the prediction of debris population from a single breakup event specifies effectively when, where and how optical measurements using ground-based telescopes should conducted. Second, the prediction of debris motion in a series of successive images clearly distinguishes fragments generated by the target breakup event from other detected objects that have originated from other breakup events. This practical method has been verified by applying for two confirmed breakups in the geostationary region [19,20].

This practical method can be applied to an orbital anomaly, which may have release fragments with uncertainty about the time to the order for several weeks. Fig. 5 demonstrates observation planning to search possible fragments released from a known orbital anomaly of a US Titan IIIC Transtage in February 1994. Fig. 5 provides time-integrated distribution of possible fragments from the anomaly, where most fragments will be detected, as a function of geocentric right ascension and declination. Deep-colored area represents a region where detection rate is high. Fig. 5 also masks invisible region from a telescope in Japan, and overlays the Earth shadow at the nominal geostationary altitude further. If a 1-degree field-of-view telescope keeps looking at the point where most fragments will be detected for 6 hours, then a detection rate can be up to 7.96 fragments/hour. On the assumption that a declination range between –20 degrees and +20 degrees is surveyed with the same field-of-view telescope, the duration necessary for the entire survey observation may take at least 960 hours, resulting in a detection rate of 0.25 fragments/hour. The detection rate of approximately 30 times can be expected by this practical method.

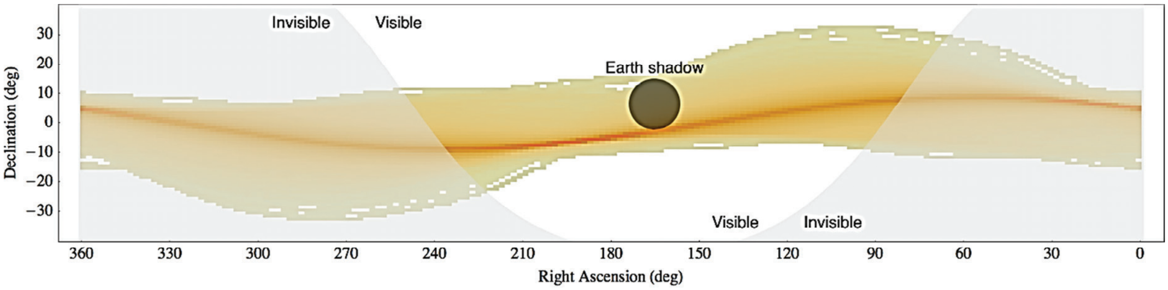

Fig. 5. Observation planning to search fragments from the US Titan IIIC Transtage using the JAXA Nyukasa Observatory in Nagano Prefecture.

7. In-situ Measurements

Kyushu University has initiated IDEA the project for in-situ debris environmental awareness, aiming at a prompt and clear understanding of the current and future micron-size debris environment in the low Earth orbit region [21]. Orbital debris, even smaller than 1 mm, may cause a fatal damage on a spacecraft. Therefore, knowledge on micron-size debris should be incorporated in design of spacecraft. However, the current micron-size debris environment has not been defined well because measurements are quite limited in terms of orbital regimes and not continuously available yet. The latest knowledge on micron-size debris from recent major breakups such as Chinese anti-satellite missile test using Fengyun-1C in January 2007 and US Iridium 33 and Russian Cosmos 2251 accidental collision in February 2009 may not be enough to understand the current environment. Knowledge is necessary to be dynamically updated based on measurements in the actual environment. Thus, the IDEA project proposes to deploy a group of micro satellites into any orbital regimes to be monitored, establishing an in-situ and near real-time measurements network. Once the IDEA measurement network is established, knowledge on micron-size debris in the orbital regimes becomes continuously available to define and dynamically update the current micron-size debris environment.

The IDEA measurement network can realize a high temporal-spatial resolution capability to cognize environmental change as a result of a breakup. Fig. 6 demonstrates the time-averaged flux per unit area per day of fragments down to 100 μm from the Chinese anti-satellite missile test in January 2007 to a satellite in a Sun-synchronous orbit as a function of geocentric right ascension and declination. It can be observed from Fig. 6 that the time-averaged flux of fragments from the test to the satellite has two peaks along the orbit. The two peaks are exactly located on the line of nodes on the orbital plane of the satellite, intersected by the orbit in which the test was conducted. If one of the IDEA satellites ideally identifies the peak locations, then the orbital plane on which the test was conducted can be also identified. If three of the IDEA satellites ideally identify the peak locations, then the location at which the test was conducted can be also identified.

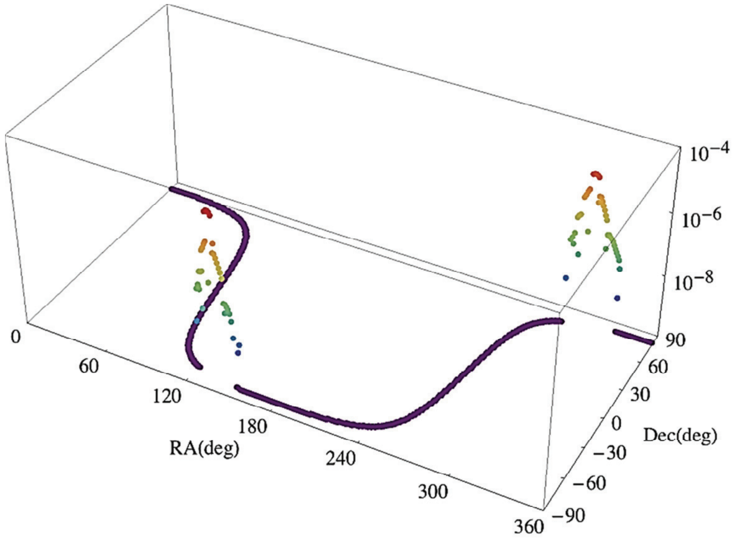

Fig. 6. Time-averaged flux per unit area per day of fragments down to 100 μm from the Chinese anti-satellite missile test on 11 January 2007 to a satellite in a Sun-synchronous orbit as a function of geocentric right ascension (RA) and declination (Dec).

8. Conclusion

This paper briefly introduced efforts into orbital debris modeling and applications at Kyushu University. The orbital debris modeling, which describes debris generation and orbit propagation, can build orbital debris evolutionary models as essential tools to predict the current or future orbital debris populations, and also to discuss what and how to do for orbital debris mitigation and environmental remediation. The orbital debris modeling can also devise an effective search strategy applicable for breakup fragments in the geostationary region using ground-based optical sensors, and to evaluate the effectiveness of space-based measurements of objects not tracked from the ground, both to contribute to space situational awareness. Another application of the orbital debris modeling is to estimate attitude motion of space objects to be removed for environmental remediation. Kyushu University will pursue researches on the orbital debris modeling and applications for sustainable space development and utilization for humankind.

Acknowledgements

The author wishes to acknowledge students, alumnae and alumni for their outstanding works on orbital debris modeling and applications at Kyushu University. The author also wishes to acknowledge IHI Corporation, Japan Aerospace Exploration Agency, Japan Spaceguard Association, Mitsubishi Heavy Industries, Ltd., NASA Orbital Debris Program Office, and National Central University for their contributions and supports to orbital debris modeling and applications at Kyushu University.

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