STABILITY OF THE FUTURE LEO ENVIRONMENT – AN IADC COMPARISON STUDY

J.-C. Liou(1), A.K. Anilkumar(2), B. Bastida Virgili(3), T. Hanada(4), H. Krag(3), H. Lewis(5), M.X.J. Raj(2), M.M. Rao(2), A. Rossi(6), R.K. Sharma(2)

(1)NASA Johnson Space Center, Houston, TX 77058, USA, Email: jer-chyi.liou-1@nasa,gov
(2)Indian Space Research Organisation, India
(3)European Space Agency, European Space Operations Centre, Germany
(4)Kyushu University, Japan
(5)University of Southampton, United Kingdom
(6)IFAC-CNR, Italy

ABSTRACT

Recent modeling studies of the orbital debris (OD) population in low Earth orbit (LEO) have suggested that the current environment has already reached the level of instability. Mitigation measures commonly adopted by the international space community, including those of the Inter-Agency Space Debris Coordination Committee (IADC) and the United Nations, may be insufficient to stop the future population growth. In response to this new finding, an official IADC modeling study was conducted to assess the stability of the current LEO debris population. Results from six different models were consistent - even with a 90% compliance of the commonly-adopted mitigation measures and no future explosion, the simulated LEO debris population increased by an average of approximately 30% in the next 200 years. Catastrophic collisions are expected to occur every 5 to 9 years. Remediation measures, such as active debris removal, should be considered to stabilize the future LEO environment.

1 INTRODUCTION

The instability of the orbital debris (OD) population problem, the "Kessler Syndrome", was predicted by Kessler and Cour-Palais more than 30 years ago [1]. Recent modeling studies of the OD population in low Earth orbit (LEO, the region below 2000 km altitude) suggested that the current LEO environment had already reached the level of instability. Mitigation measures commonly adopted by the international space community, including those of the Inter-Agency Space Debris Coordination Committee (IADC) and the United Nations (UN), may be insufficient to stop the future population growth. In response to this new finding, an official IADC modeling study was conducted in 2008 to assess the stability of the current LEO orbital debris (OD) population. Study participants were ASI, BNSC (now UKSA), ESA, JAXA and NASA. The study's goal was to investigate the stability of the LEO debris environment using the 1 January 2006 population as the initial condition. The 200-year future projection adopted a "best case" scenario where no new launches and no explosion beyond 1 January 2006 were allowed. At the conclusion of the internal study in March 2009, a follow-up study, based on an updated environment (including fragments from Fengyun-1C, Cosmos 2251, and Iridium 33), a more realistic future lunch traffic cycle, and post-mission disposal implementation, was recommended. The Steering Group (SG) also asked WG2 to designate the follow-up study as an official Action Item, AI 27.1, because of its potential significance.

The objective of AI 27.1 was to assess the stability of the LEO debris population and reach a consensus on the need to use active debris removal (ADR) to stabilize the future environment. Participants included ASI, ESA, ISRO, JAXA, NASA, and UKSA. The study was coordinated and led by NASA. Details of AI 27.1, its outcomes, and recommendations are summarized in this paper.

2 STUDY PRINCIPLES AND SCENARIO

In order to constrain the many degrees of freedom within the study, some reasonable assumptions were made. First, it was assumed that future launch traffic could be represented by the repetition of the 2001 to 2009 traffic cycle. Second, the commonly-adopted mitigation measures were assumed to be well-implemented. In particular, a compliance of 90% with the post-mission disposal "25-year" rule for payloads (i.e., spacecraft, S/C) and upper stages (i.e., rocket bodies, R/Bs) and a 100% success for passivation (i.e., no future explosions) were assumed. However, collision avoidance maneuvers were not allowed, in keeping with previous WG2 modeling studies. In addition, an 8-year mission lifetime for payloads launched after 1 May 2009 was uniformly adopted.

Each participating member agency was asked to use its official, or best, models for solar flux prediction, orbit propagation, and collision probability calculation for the study. These elements are described for each model in later sections. Collision probability calculations were

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

limited to 10 cm and larger objects. The NASA Standard Breakup Model (Johnson et al., 2001) was used by all participants for their future projections, as it was determined that participants did not employ any other fragmentation model. The participants were encouraged to conduct as many Monte Carlo (MC) simulations as time and resources allowed to achieve better statistical results. Finally, the study conclusions were drawn primarily from the average results of each participating model, determined through MC simulations.

The study scenario required models to perform future projections of the 10 cm and larger LEO-crossing population for 200 years past the 1 May 2009 reference epoch. Launch traffic was added to the projection according to the repeated 2001 to 2009 traffic cycle, with 8-year operational lifetimes assumed for payloads. At the end of this 8-year period, 90% of payloads were placed into decay orbits with a nominal, remaining lifetime of 25 years. Where it was determined that a transfer to a graveyard orbit above LEO was cost-effective, objects were removed from the simulation immediately. Rocket bodies launched after 1 May 2009 were also transferred immediately to 25-year decay orbits with the same success rate. Future explosions were not allowed (based on the assumption of good implementation of passivation measures) and collision avoidance maneuvers were not permitted.

3 INITIAL POPULATION AND MODEL DESCRIPTIONS

3.1 Initial Population

The initial population used for the study was provided by ESA and was generated using the MASTER-2009 model. The population included all 10 cm and larger LEO-crossing objects on 1 May 2009, although high area-to-mass ratio (A/M) multi-layer insulation fragments were excluded. LEO-crossing objects are those with perigee altitudes below 2000 km. Each object was listed individually and was categorized as either a rocket body, payload, mission-related debris, or fragmentation debris. Launch dates for all rocket bodies, payloads, and mission-related debris launched between 1 May 2001 and 30 April 2009 were also provided by ESA, enabling an 8-year traffic cycle to be generated and repeated for the future projection.

Fig. 1 shows the spatial density distribution as a function of altitude. The fragments produced by the Fengyun-1C fragmentation in January 2007 and the Iridium 33-Cosmos 2251 collision in February 2009 have contributed to the peak in spatial density between 700 km and 1000 km.

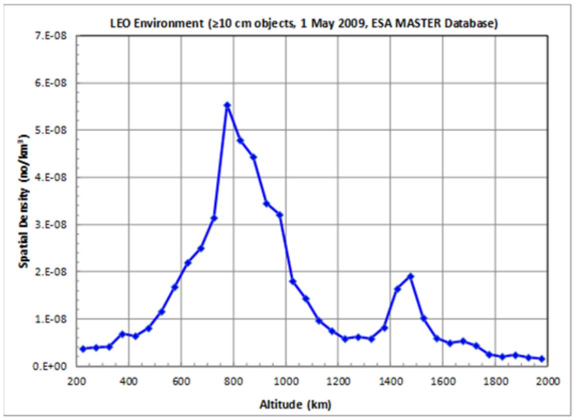

Figure 1. Spatial density of the initial population as a function of altitude.

3.2 Model Descriptions

3.2.1 ASI Model - SDM

Originally developed in the early 1990s under an ESA Contract, the Space Debris Mitigation long-term analysis program (SDM) recently has been fully revised, redesigned, and upgraded to version 4.1 [2-5]. SDM 4.1 was used for AI 27.1. The model is a full three-dimensional LEO to GEO simulation code, including advanced features that make it ideal for long term studies of every orbital regime, with particular attention to the Medium Earth Orbit (MEO) and Geosynchronous orbit (GEO) regions. All the main source and sink mechanisms influencing the orbital debris population down to the size of 1 mm are modeled inside SDM 4.1.

In SDM 4.1 three orbital propagators are implemented and can be selected according to the different orbital regimes and to the accuracy required. SDM 4.1 can use two different approaches to calculate the collision rate between the orbiting objects: the CUBE algorithm, developed at NASA/JSC, and a fully analytical algorithm based on Opik's theory to evaluate the collision probability between objects in LEO. Several models can be used to simulate explosion and collision events, the default one being the NASA Standard Breakup Model.

SDM 4.1 has an extremely detailed traffic model allowing the simulation of complex mitigation scenarios in every orbital regime (including MEO Global Navigation Satellite System, GNSS), constellations management, collision avoidance, and active debris removal.

3.2.2 ESA Model - DELTA

ESA's Debris Environment Long-Term Analysis (DELTA) software was originally developed by

QinetiQ [6-8]. DELTA is a three-dimensional, semi-deterministic model, which in its entirety allows a user to investigate the evolution of the orbital debris environment and the associated mission collision risks for the low, medium, and geosynchronous orbit regions. DELTA is able to examine the long-term effects of different future traffic profiles and debris mitigation measures, such as passivation and disposal at end-of-life [9]. The most recent available version, v3.0, has been modified to add the active debris removal capabilities. The current version is, therefore, v3.1.

DELTA uses an initial population as input and forecasts all objects larger than 1 mm in size. The population is described by representative objects, evolved with a fast analytical orbit propagator that takes into account the main perturbation sources. The high fidelity of the DELTA model is ensured by using a set of detailed future traffic models for launch, explosion and solid rocket motor firing activity. Each traffic model is based on the historical activity of the eight preceding years. The collision event prediction uses a target-centered approach, developed to stochastically predict impacts for large target objects (mass higher than 50 kg) within the DELTA population. The fragmentation, or break-up, model used is based on the NASA Standard Breakup Model.

3.2.3 ISRO Model - KSCPROP

ISRO's long-term debris environment projection model is named KSCPROP. Orbit computations in KSCPROP can be carried out for 200 years, revolution by revolution, using the non-singular, fourth-order analytical theory for the motion of near-Earth satellite orbits. The air drag effects are generated in terms of uniformly regular Kustaanheimo and Stiefel (KS) canonical elements. A diurnally-varying oblate atmosphere is considered with constant density scale height. The theory is valid for orbits with eccentricities less than 0.2 [10]. Monthly averaged values of F10.7, also provided for 200 years, are utilized. The secular effects of the Earth's oblateness (J_2) in argument of perigee (ω), right ascension of ascending node (Ω), and long-term perturbations due to J_2 ,J_3, J_4 in eccentricity, are added after every revolution. The Jacchia 1977 atmospheric density model also is utilized to compute the values of the density and density scale height at perigee after every revolution.

Conjunction assessments are carried out by incorporating the apogee-perigee filter, geometric filter, and time filter, based on Hoots et al. [11]. The collisions between any two objects are simulated. The NASA Standard Breakup Model is used to find out the orbital characteristics of the collision fragments. Results of 17074 objects for 200 years were analyzed.

Monte Carlo simulations are carried out by considering various parameter perturbations and also collision probability variations. The parameters considered in MC simulations are ballistic coefficient, F10.7 and Ap with three sigma dispersion = 10%, assuming Gaussian distribution. Other important parameters considered in MC are uncertainties in distribution parameters in breakup model, variations in size, mass, delta velocity of fragments. 40 MC runs Using ISRO parallel computing facility available in Vikram Sarabhai Space Centre. The outputs monitored and analyzed through MC simulations are (1) number of objects decayed at the end of the each year and (2) the orbital parameters of the objects.

3.2.4 JAXA Model - LEODEEM

JAXA and the Kyushu University (KU) have jointly developed LEODEEM, an orbital debris evolutionary model for the low Earth orbit region. The KU has maintained and operated LEODEEM under contract with JAXA [12].

LEODEEM originally tracked all intact objects such as spacecraft and rocket bodies, whereas mission-related objects and fragmentation debris were binned in perigee and apogee radii and inclination, and were propagated as representative particles randomly selected, to reduce the time needed for long-term projection [12]. For AI 27.1, LEODEEM was revised to track individually all objects larger than 10 cm in size.

LEODEEM has adopted an analytical orbit integrator independently developed at KU. Orbit perturbations include the zonal harmonics of the Earth's gravitational attraction (up to four orders), gravitational attractions due to the Sun and Moon, the solar radiation pressure effects, and the atmospheric drag (coupled with solar activities). LEODEEM has adopted the VSOP87 planetary theory to obtain the position of the Sun with respect to the Earth, and the ELP2000 lunar theory to obtain the position of the Moon with respect to the Earth [13].

The probability of collision is estimated for the overlapping portion between the spheres of two colliding objects [14]. Once a collision is identified, LEODEEM generates fragments based on the NASA Standard Breakup Model.

3.2.5 NASA Model - LEGEND

LEGEND, a LEO-to-GEO Environment Debris model, is the tool used by the NASA Orbital Debris Program Office (ODPO) for long-term debris environment studies [15-16]. Its recent applications include an investigation of the instability of the debris population in LEO [17], and the modeling of the effectiveness of active debris removal [18-19]. The historical component in LEGEND adopts a deterministic approach to mimic the known historical populations. Launched rocket bodies, spacecraft, and mission-related debris are added to the simulated environment based on a comprehensive

ODPO internal database. Known historical breakup events are reproduced and fragments are created with the NASA Standard Breakup. The future projection components of LEGEND include a user-specified launch traffic cycle, user-specified mitigation and ADR scenarios, explosions, and collisions. Collision probabilities among orbiting objects are estimated with a fast, pair-wise comparison algorithm [16].

Two propagators are used in LEGEND. One is for GEO objects and the other is for LEO and GTO objects. Perturbations included are Earth's J_2, J_3, J_4, solar–lunar gravitational perturbations, atmospheric drag, solar radiation pressure, and Earth's shadow effects. Historical daily solar flux F10.7 values are combined with the J77 atmospheric model for the drag calculation [20]. The solar flux F10.7 values used in the projection period have two components: a short-term projection obtained from the NOAA Space Environment Center and a long-term projection. The latter was a repeat of a sixth-order sine and cosine functional fit to Solar Cycles 18-23.

3.2.6 UK Space Agency Model - DAMAGE

The University of Southampton's Debris Analysis and Monitoring Architecture for the Geosynchronous Environment (DAMAGE) is a three-dimensional computational model that was initially developed to simulate the debris population in GEO but has since been upgraded to allow investigations of the full LEO to GEO debris environment. DAMAGE has been used to investigate the long-term stability of super-synchronous disposal orbits [21], the effectiveness of different removal criteria for ADR [22], the implications of space climate change for space debris mitigation [23-24], understanding the effect of debris on spacecraft operations [25], and for calibrating a Fast Debris Evolution (FADE) model [26].

DAMAGE is a semi-deterministic model implemented in C++, running under Microsoft Windows and using OpenGL for graphical support. A fast, pair-wise algorithm based on the 'Cube' approach adopted in NASA's LEGEND model [16] is used to determine the collision probability for all orbiting objects. DAMAGE makes use of the NASA Standard Breakup Model to generate fragmentation debris arising from collisions and explosions.

DAMAGE employs a fast, semi-analytical orbital propagator to update the orbital elements of objects within the environment. This propagator includes orbital perturbations due to Earth gravity harmonics, J_2, J_3, and $J_{2,2}$, lunisolar gravitational perturbations, solar radiation pressure, and atmospheric drag. The drag model assumes a rotating, oblate atmosphere with density and density scale height values taken from the 1972 COSPAR International Reference Atmosphere (CIRA). Atmospheric density and scale height values are stored as look-up tables within DAMAGE for discrete altitudes and exospheric temperatures, and projected solar activity is described using a sinusoidal model. To obtain solar activity values throughout the projection period, log-linear interpolation is used to extract density and scale height estimates from the look-up tables for the perigees of all objects within the LEO region.

Projections into the future of the debris population ≥10 cm are performed using an MC approach to account for stochastic elements within the model and to establish reliable statistics.

3.3 Solar Flux Projection Models

The solar flux projections used by participating agencies for the period from 2010 through 2060 are shown in Fig. 2. There is reasonable correlation in terms of the magnitude and phase. The UK model was adopted by JAXA/KU's LEODEEM for the simulations.

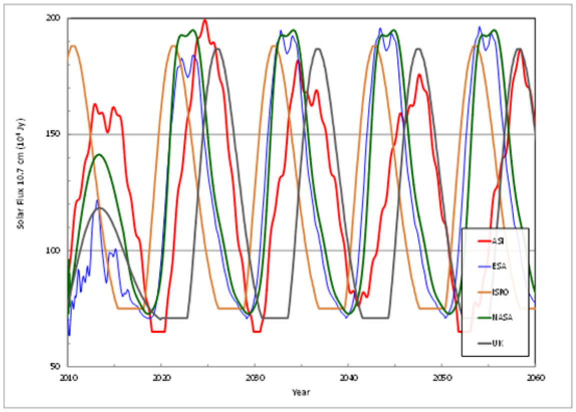

Figure 2. Solar flux projections used by participating agencies for AI 27.1. Only the period from 2010 through 2060 is shown for clarity.

4 STUDY RESULTS

The study results are presented below. The number of MC simulations employed by each model to generate these results is shown in Tab. 1. The total MC runs of the six models is 725.

Table 1. Number of Monte Carlo (MC) simulations performed by participating models.

Agency	ASI	ESA	ISRO	JAXA	NASA	UKSA
Model	SDM	DELTA	KSCPROP	LEODEEM	LEGEND	DAMAGE
MC Runs	275	100	40	60	150	100

The projections of the total LEO population through the year 2209, assuming no future explosion and a 90% compliance of the commonly adopted mitigation measures, from the six models are summarized in Fig. 3.

In all cases, the models predict a population growth. The average increase is 30% in 200 years. The short-term fluctuation, occurring on a timescale of approximately 11 years, is due to the solar flux cycle.

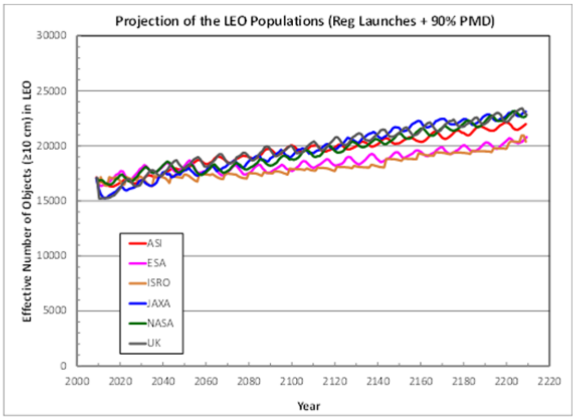

Figure 3. Effective numbers of objects 10 cm and larger in LEO predicted by the six different models. All models assumed no future explosion and 90% compliance of the commonly adopted mitigation measures.

The projections by individual models, including population breakdown and the 1-sigma standard deviation for the total, follow very similar trends. One example is given in Fig. 4.

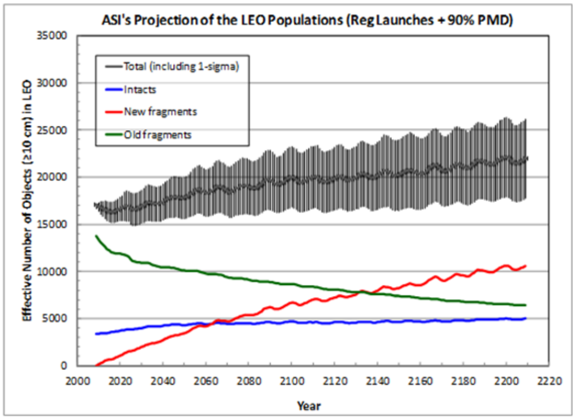

Figure 4. ASI's projection of the future LEO population.

Fig. 5 shows the cumulative number of catastrophic collisions occurring within the 200-year projection period. Catastrophic collisions, such as the one between Iridium 33 and Cosmos 2251 in 2009, result in the complete fragmentation of the objects involved and generate a significant amount of debris. They are the main driver for future population increases. The steepest curve (UKSA) represents a catastrophic collision frequency of one event every 5 years, whereas the shallowest curve (ISRO) represents a frequency of one event every 9 years. All model predictions for catastrophic collisions show a good fit with a straight line for the next 200 years (average correlation coefficient = 0.99). Catastrophic collisions occur primarily at altitudes of 700-800 km, 900-1000 km.

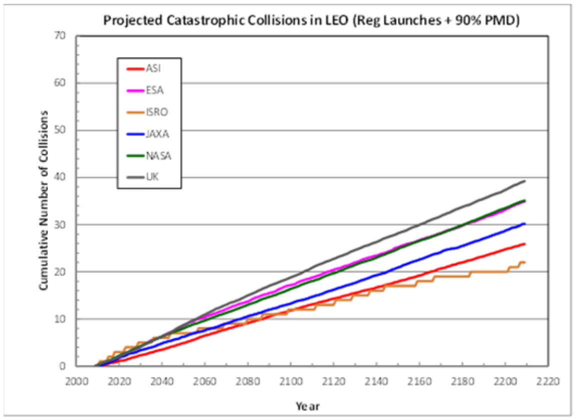

Figure 5. Cumulative numbers of catastrophic collisions predicted by the six models.

The population increase at the end of the 200-year projection (the year 2209) predicted by the six models are shown in Fig. 6. The initial environment (year 2009) is also included for comparison. The number of objects at any altitude, at a given point in time, is a balance between sources and sink. The former includes new launches, fragments generated from new collisions, and fragments decayed from higher altitudes (due to atmospheric drag) while the latter includes objects decayed toward lower altitudes (due to atmospheric drag). Overall, there is a general population increase above 800km.

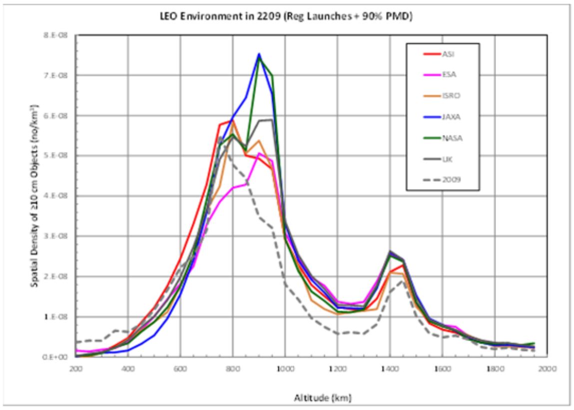

Figure 6. The initial (dashed curve) and projected LEO environment in year 2209.

Tab. 2 provides additional details of the model predictions. Of the 725 MC simulations, 633 (87%) resulted in a net population increase in 200 years. The overall MC average is a 30% increase in 200 years.

Table 2. Summary of the projected LEO population increase based on regular launches and a 90% compliance of the commonly-adopted mitigation measures.

Agency	ASI	ESA	ISRO	JAXA	NASA	UKSA	All
Model	SDM	DELTA	KSCPROP	LEODEEM	LEGEND	DAMAGE	–
MC Runs	275	100	40	60	150	100	725
% of MC runs with N_{2209}>N_{2009}	88% (242/275)	75% (75/100)	90% (36/40)	88% (53/60)	89% (133/150)	94% (94/100)	87% (633/725)
Average Change in Population by 2209	+29%	+22%	+19%	+36%	+33%	+33%	+30%

5 Summary

The IADC WG2 initiated AI 27.1 in 2009 to investigate the stability of the debris population in LEO. Six member agencies, ASI, ESA, ISRO, JAXA, NASA, and UKSA, participated in the study. The initial OD population (objects 10 cm and larger) for the year 2009 and a nominal future launch traffic cycle were defined and provided by ESA. Each participating member then used their best models to simulate the future environment, assuming nominal launches and a 90% compliance of the commonly-adopted mitigation measures and no future explosion, through year 2209. A total of 725 MC runs were carried out. Analyses of the results indicate that the six model predictions are consistent with one another. Even with a 90% implementation of the commonly-adopted mitigation measures and no future explosion, the LEO debris populations are expected to increase by an average of 30% in the next 200 years. The population growth is primarily driven by catastrophic collisions between 700 and 1000 km altitudes and such collisions are likely to occur every 5 to 9 years.

The AI 27.1 results confirm the instability of the current LEO debris population. They also highlight two key elements for the long-term sustainability of the future LEO environment. First, compliance of the mitigation measures, such as the 25-year rule, is the first defense against the OD population increase. The need for a full compliance must be emphasized. The 90%-compliance assumption made in the simulations is certainly higher than the current reality. If the international space community cannot reach this level soon, future debris population growth will be far worse than the AI 27.1 study results, and it will certainly make future OD environment management much more difficult. Second, to stabilize the LEO environment, more aggressive measures, such as active debris removal, must be considered. Remediation of the environment after more than 50 years of space activities is complex, difficult, and will likely require a tremendous amount of resources and international cooperation. The international community should initiate an effort to investigate the benefits of environment remediation, explore various options, and support the development of the most cost-effective technologies in preparation for actions to better preserve the near-Earth environment for future generations.

6 REFERENCE

1. Kessler, D.J. & Cour-Palais, B.G. (1978). Collision Frequency of Artificial Satellites: The Creation of a Debris Belt. *JGR,* **83**(A6), 2637-2646.
2. Rossi, A., Cordelli, A., Pardini, C., Anselmo, L., and Farinella, P. (1994). Modelling the Space Debris Environment: Two New Computer Codes, Advances in the Astronautical Sciences, Spaceflight Mechanics 1995, 1217-1231.
3. Rossi, A., Anselmo, L., Pardini, C. & Valsecchi, G.B. (2004). Final Report, Upgrade of the Semi-Deterministic Model to Study the Long Term Evolution of the Space Debris. ESA/ESOC Contract No. 15857/01/D/HK(SC), ISTI/CNR. Pisa, Italy.
4. Rossi, A., Anselmo, L., Pardini, C. and Valsecchi, G.B., (2009). Final Report, Semi-Deterministic Model. ESA/ESOC Contract No. 18423/04/D/HK, ISTI/CNR. Pisa, Italy.
5. Rossi, A., Anselmo, L., Pardini, C., Jehn, R. (2009). The new Space Debris Mitigation (SDM 4.0) long term evolution code, Proceedings of the Fifth European Conference on Space Debris, Darmstadt, Germany, 30 March-2 April 2009, CD-ROM SP-672.
6. Walker, R., Martin, C. E., Stokes, P. H. Wilkinson, J. E., and Klinkrad, H. (2001). Analysis of the effectiveness of space debris mitigation measures using the Delta model, *Adv. Space Res*. **28**, 1437-1445.

7. Walker, R. and Martin, C. E. (2004). Cost-effective and robust mitigation of space debris in low earth orbit, *Adv. Space Res*. **34**, 1233-1240.

8. Martin, C., Walker, R., and Klinkrad, H. (2004). The sensitivity of the ESA DELTA model, *Adv. Space Res.* **34**, 969-974.

9. Bastida Virgili, B. and H. Krag (2009). Strategies for active removal in LEO, Proceedings of the Fifth European Conference on Space Debris, Darmstadt, Germany, 30 March-2 April 2009, CD-ROM SP-672.

10. Raj, X. J. and Sharma, R. K. (2009). Prediction of satellite orbits contraction due to diurnally varying oblate atmosphere and altitude dependent scale height using KS canonical elements, Planetary and Space Science, 57, 1312-1320.

11. Hoots, F. R., Crawford, L. L., and Roehrich, R. L. (1984). An analytic method to determine future close approaches between satellites", *Celestial Mechanics* **33**, 143-158.

12. Hanada, T., Ariyoshi, Y., Miyazaki, K., Maniwa, K., Murakami, J., and Kawamoto, S. (2009). Orbital debris modeling at Kyushu University, *J. Space Technology and Science* **24** (2), 23-35.

13. Narumi, T. and Hanada, T. (2007). New orbit propagator to be used in orbital debris evolutionary models, Memoirs of the Faculty of Engineering, Kyushu University, Vol.67, No.4, 235-254.

14. Hanada, T. and Yasaka, T. (2004). GEODEEM 3.0: Updated Kyushu University GEO model, Proceedings of the 24th International Symposium on Space Technology and Science, Miyazaki, Japan, May 30-June 6, 946-951.

15. Liou, J.-C., Hall, D.T., Krisko, P.H., and Opiela, J.N. (2004). LEGEND – A three-dimensional LEO-to-GEO debris evolutionary model. *Adv. Space Res*. **34**, 5, 981-986.

16. Liou, J.-C. (2006). Collision activities in the future orbital debris environment, *Adv. Space Res*. **38**, 9, 2102-2106.

17. Liou, J.-C. and Johnson, N. L. (2006). Risks in space from orbiting debris, *Science* **311**, 340-341.

18. Liou, J.-C. and Johnson, N. L. (2009). A sensitivity study of the effectiveness of active debris removal in LEO, *Acta Astronautica 64*, 236-243.

19. Liou, J.-C. (2011). An active debris removal parametric study for LEO environment remediation, *Adv. Space Res*. **47**, 1865-1876.

20. Jacchia, L. G. (1977). Thermospheric Temperature, Density, and Composition: New model, Smithsonian Special Report SAO 375, Cambridge, MA.

21. Lewis, H. G., Swinerd, G. G., Martin, C. E., and Campbell, W. S. (2004). The stability of disposal orbits at super-synchronous altitudes, *Acta Astronautica* **55**(3-9), 299-310.

22. Lewis, H. G., Swinerd, G. G., Newland, R. J., and Saunders, A., Active removal study for on-orbit debris using DAMAGE (2009). In Proceedings of the Fifth European Conference on Space Debris, Darmstadt, Germany, 30 March-2 April 2009, European Space Agency Publication SP-672 (CD).

23. Lewis, H. G., Swinerd, G. G., Ellis, C. S., and Martin, C. E. (2005). Response of the space debris environment to greenhouse cooling, in Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April, 2005, European Space Agency Publication SP-587, 243-248.

24. Lewis, H. G., A. Saunders, Swinerd, G. G., and Newland, R. J. (2011). Effect of thermospheric contraction on remediation of the near-Earth space debris environment, *J. Geophys. Res*. (in press).

25. Lewis, H. G., Swinerd, G. G., and Newland, R. J. (2011). The space debris environment: future evolution. *The Aeronautical Journal* (in press).

26. Lewis, H. G., Swinerd, G. G., Newland, R. J., and A. Saunders (2009). The fast debris evolution model, *Adv. Space. Res*. **44**(5), 568-578.