Earth Satellite Population Instability: Underscoring the Need for Debris Mitigation

J.-C. Liou[1] and N. L. Johnson[2]

[1] *Mail Code JE104, ESCG/ERC, 2224 Bay Area Boulevard, Box 7, Houston, Texas 77058, USA.*

[2] *Orbital Debris Program Office, NASA Johnson Space Center, Houston, Texas 77058, USA.*

Correspondence and requests for materials should be addressed to:

Dr. J.-C. Liou
Mail Code JE104, ESCG/ERC
2224 Bay Area Boulevard, Box 7
Houston, Texas 77058, USA
Tel: (281) 244-5975
FAX: (281) 244-5031
Email: jer-chyi.liou1@jsc.nasa.gov

A recent study by NASA indicates that the implementation of international orbital debris mitigation measures alone will not prevent a significant increase in the artificial Earth satellite population, beginning in the second half of this century. Whereas the focus of the aerospace community for the past 25 years has been on the curtailment of the generation of long-lived orbital debris, active remediation of the current orbital debris population should now be reconsidered to help preserve near-Earth space for future generations. In particular, we show in this paper that even if launch operations were to cease today, the population of space debris would continue to grow. Further, proposed remediation techniques do not appear to offer a viable solution. We therefore recommend that, while the aerospace community maintains the current debris-limiting mission regulations and postmission disposal procedures, future emphasis should be placed on finding new remediation technologies for solving this growing problem.

Since the launch of Sputnik 1, space activities have created an orbital debris environment that poses increasing impact risks to existing space systems, including human space flight and robotic missions (*1*, *2*). Currently, more than 9,000 Earth orbiting man-made objects (including many breakup fragments), with a combined mass exceeding 5 million kilograms, are tracked by the US Space Surveillance Network and maintained in the US satellite catalog (*3*-*5*). Three accidental collisions between cataloged satellites during the period from late 1991 to early 2005 have already been documented (*6*), although fortunately none resulted in the creation of large, trackable debris clouds.

Several studies conducted during 1991-2001 demonstrated, with assumed future launch rates, the unintended growth potential of the Earth satellite population, resulting from random, accidental collisions among resident space objects (*7-13*). In some low Earth orbit (LEO) altitude regimes where the number density of satellites is above a critical spatial density, the production rate of new satellites (*i.e.*, debris) due to collisions exceeds the loss of objects due to orbital decay.

NASA's evolutionary satellite population model LEGEND (LEO-to-GEO Environment Debris model), developed by the Orbital Debris Program Office at the NASA Lyndon B. Johnson Space Center, is a high fidelity three-dimensional physical model that is capable of simulating the historical satellite environment, as well as the evolution of future debris populations (*14*, *15*). The subject study assumed no rocket bodies and spacecraft were launched after December 2004, and no future disposal maneuvers were allowed for existing spacecraft, few of which currently have such a capability. The rate of satellite explosions would naturally decrease to zero within a few decades as the current satellite population ages.

The LEGEND future projection adopts a Monte Carlo approach to simulate future on-orbit explosions and collisions. Within a given projection time step, once the explosion probability is estimated for an intact object, a random number is drawn and compared with the probability to determine if an explosion would occur. A similar procedure is applied to collisions for each pair of target and projectile involved within the same time step. Due to the nature of the Monte Carlo process, multiple projection runs must be performed and analyzed before one can draw reliable and meaningful conclusions from the outcome. A total of fifty, 200-year future projection Monte Carlo simulations were executed and evaluated (*16*).

The simulated 10 cm and larger debris populations in LEO (defined as the region between 200 and 2000 km altitudes) between 1957 and the end of a 200-year future projection period indicate that collision fragments replace other decaying debris (due to atmospheric drag and solar radiation pressure) through 2055, keeping the total LEO population approximately constant. Beyond 2055, however, the creation of new collision fragments exceeds the number of decaying debris, forcing the total satellite population to increase. An average of 18.2 collisions (10.8 catastrophic, 7.4 non-catastrophic) would be expected in the next 200 years (*17*).

As expected, a detailed analysis indicates that the predicted catastrophic collisions and the resulting population increase are non-uniform throughout LEO. About 60% of all catastrophic collisions occur between 900 and 1000 km altitudes, leading to a major population increase in the same region. There is about a factor of more than three increase for objects 10 cm and larger in 200 years, leading to a factor of ten increase in collisional probabilities among objects in this region. This population growth is due to higher spatial densities, larger and more massive rocket bodies and spacecraft with near-polar inclinations, and longer orbit decay times (compared with lower altitude regions) in this region.

Has the current debris population in the LEO region reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future? The answer is yes. Even without new launches, collisions will continue to occur in LEO over the next 200 years, primarily driven by the high collision activities in the region between 900 and 1000 km altitudes, and force the debris population to increase. In reality, the situation will undoubtedly be worse since spacecraft and their orbital stages will continue to be launched into space.

Postmission disposal of vehicles (*e.g.*, limiting postmission orbital lifetimes to less than 25 years) is now advocated by the major space-faring nations and organizations of the world, including NASA, Department of Defense, Department of Transportation, and Federal Communications Commission in the US, and the Inter-Agency Space Debris Coordination Committee (*18*), the European Space Agency, and the Japan Aerospace Exploration Agency. Postmission disposal will slow down the growth of future debris populations (*19*). However, this mitigation measure will be insufficient to constrain the Earth satellite population. Only remediation of the near-Earth environment, *i.e.*, the removal of existing large objects from orbit, can prevent the undesirable effects predicted in the present study.

For the near-term no single remediation technique appears to be both technically feasible and economically viable. Electrodynamic tethers or drag enhancement structures could rapidly accelerate the orbital decay of decommissioned spacecraft and rocket bodies, but attaching such devices to the satellites with conventional robotic means would incur excessive costs in terms of kilograms removed from orbit per mission. Even if a single remediating vehicle carried several de-orbiting packages, the energy requirements to visit multiple target spacecraft, even in the same altitude and inclination regime, would normally be high due to differences in target orbital planes (*20*).

The placement of ion engines on the satellites would incur the same challenges as the previously mentioned strategies and additionally would require significant, long-term power and attitude control subsystems. Current manned spacecraft cannot reach the key orbital regimes above 600 km and are even more expensive than robotic missions. The use of ground-based lasers to perturb the orbits of the satellites is not now practical due to the considerable mass of the satellites and the consequent need to deposit extremely high amounts of energy on the vehicles to effect the necessary orbital changes.

Hence, the success of any environmental remediation policies will probably be dependent upon the development of new, cost-effective, innovative means to remove existing derelict vehicles. The development of this new technology may require both governments and the private sector working together. Without environment remediation and the wide implementation of existing orbital debris mitigation policies and guidelines, the risks to space system operations in near-Earth orbits will continue to climb.

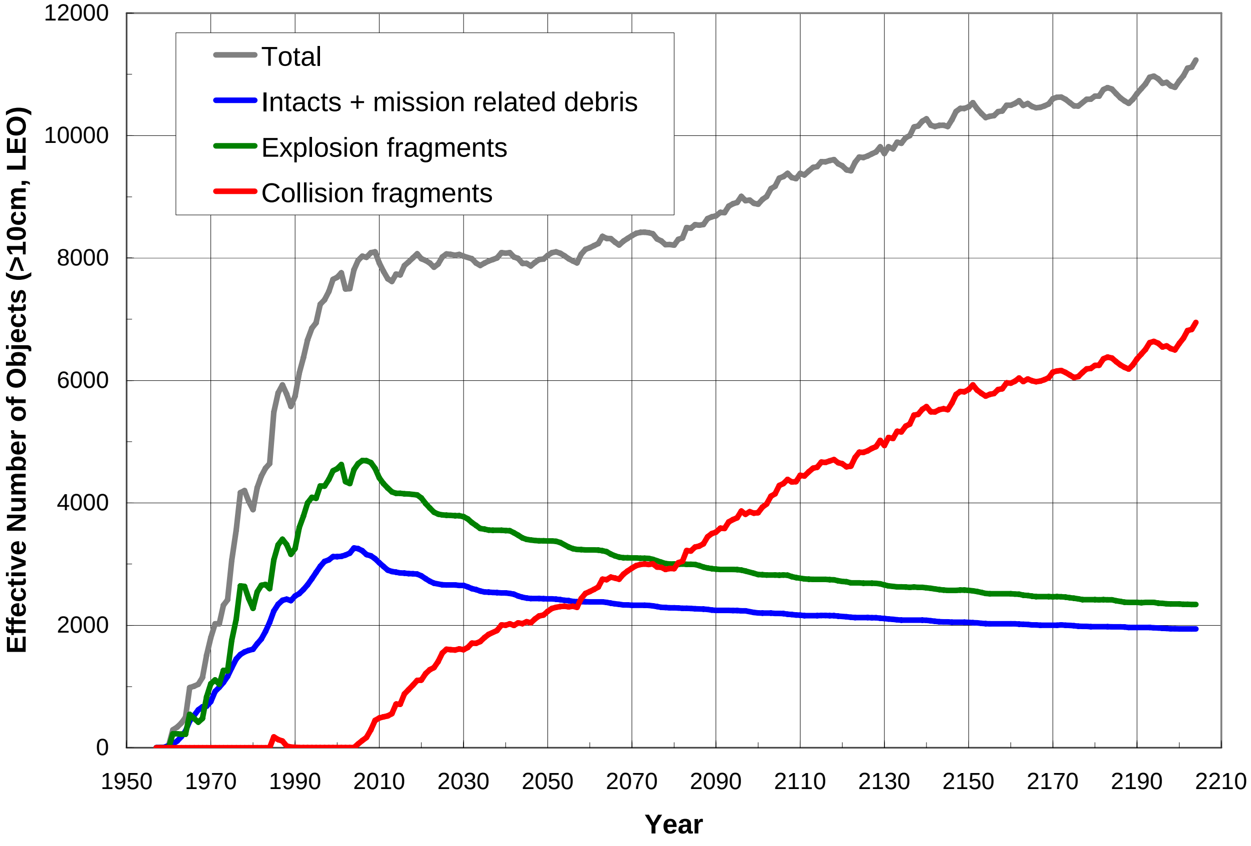
References and Notes

1. *Interagency Report on Orbital Debris*, Office of Science and Technology Policy, US National Science and Technology Council (1995).
2. Technical Report on Space Debris, Text of the Report adopted by the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space, United Nations (1999).
3. *Orbital Debris Quarterly News*, **9**, 1, p10, NASA Johnson Space Center, Houston, Texas (2005); electronic copy also available at http://www.orbitaldebris.jsc.nasa.gov/newsletter/newsletter.html.
4. *Orbital Debris Quarterly News*, **9**, 3, p10 , NASA Johnson Space Center, Houston, Texas (2005).
5. N. L. Johnson, D. O. Whitlock, P. D. Anz-Meador, E. M. Cizek, S. A. Portman, *History of On-Orbit Satellite Fragmentations*, 13th Edition. JSC-62530, NASA Johnson Space Center, Houston, Texas (2004).
6. *Orbital Debris Quarterly News*, **9**, 2, p1, NASA Johnson Space Center, Houston, Texas (2005).
7. D. J. Kessler, Collisional cascading: The limits of population growth in low Earth orbit. *Adv. Space Res.*, **11**, 12, 63-66 (1991).
8. S.-Y. Su, On runaway conditions of orbital debris environment. *Adv. Space Res.*, **13**, 8, 221-224 (1993).
9. A. Rossi, A.Cordelli, P. Farinella, L. Anselmo, Collisional evolution of the Earth's orbital debris cloud. *JGR*, **99**, E11, 23195-23210 (1994).

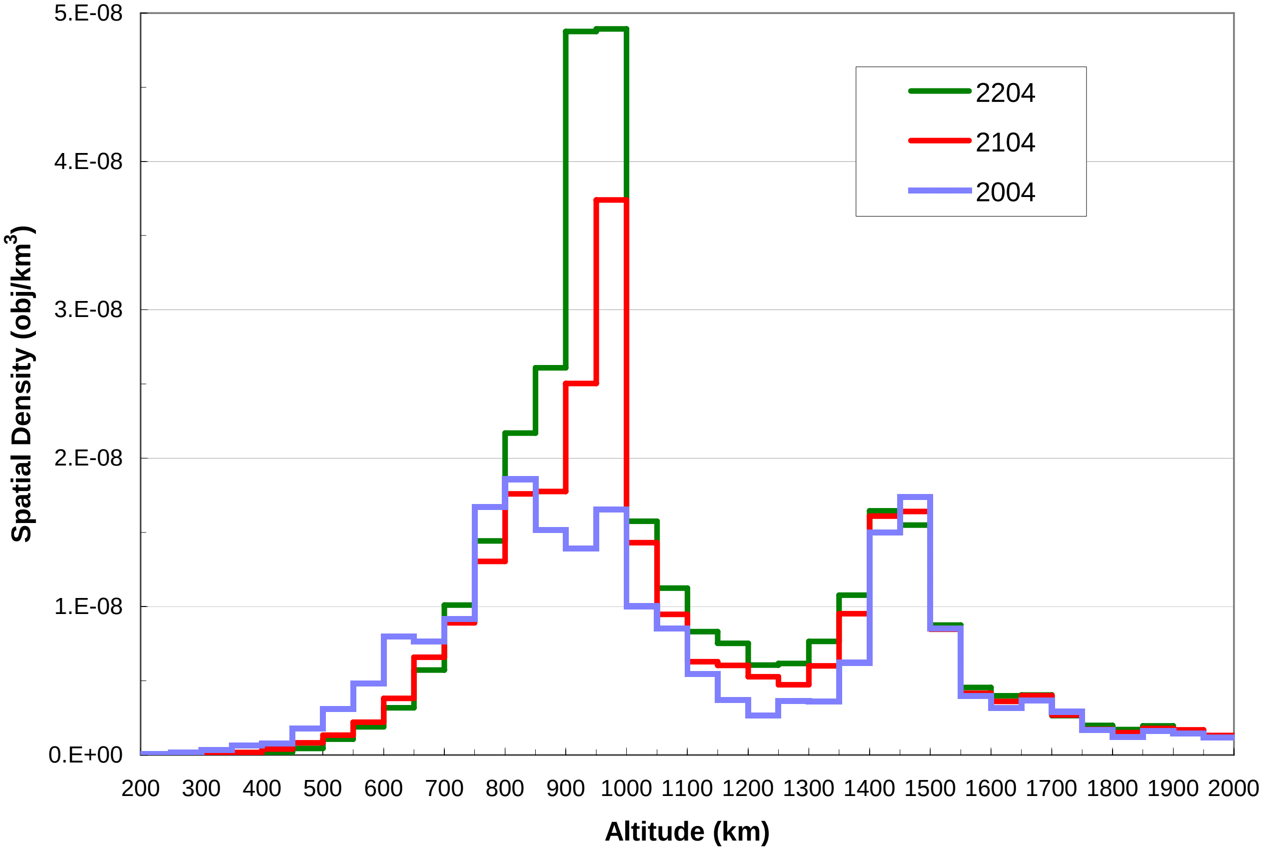
10. L. Anselmo, A. Cordelli, P. Farinella, C. Pardini., A. Rosi, Modelling the evolution of the space debris population: recent research work in Pisa, ESA SP-393, 339-344, ESOC, Darmstadt, Germany (1997).
11. D. J. Kessler, *Critical Density of Spacecraft in Low Earth Orbit*, NASA JSC-28949, NASA Johnson Space Center, Houston, Texas (2000).
12. D. J. Kessler, P. D. Anz-Meador, Critical number of spacecraft in Low Earth Orbit: Using satellite fragmentation data to evaluate the stability of the orbital debris environment. ESA SP-473, 265-272, ESOC, Darmstadt, Germany (2001).
13. P. H. Krisko, J. N. Opiela, D. J. Kessler, The critical density theory in LEO as analyzed by EVOLVE 4.0. ESA SP-473, 273-278, ESOC, Darmstadt, Germany (2001).
14. J.-C. Liou, D. T. Hall, P. H. Krisko, J. N. Opiela, LEGEND – A three-dimensional LEO-to-GEO debris evolutionary model. *Adv. Space Res.*, **34**, 5, 981-986 (2004).
15. J.-C. Liou, Collision Activities in the future orbital debris environment. *Adv. Space Res.* (doi:10.1016/j.asr.2005.06.021), in press (2005).
16. A statistical analysis of LEGEND predictions, based on the bootstrap method, indicates that the average from 50 MC runs leads to a standard error of the average on the order of 5% or less, which was sufficient for the recent study. Results presented and discussed in this article are all based on averages from 50 MC runs.
17. A catastrophic collision occurs when the ratio of impact energy to target mass exceeds 40 J/g. The outcome of a catastrophic collision is the total fragmentation of the target, *i.e.*, resident space object, whereas a non-catastrophic collision only results

in minor damage to the target and generates a small amount of debris that has minimal contribution to population growth. See also N. L. Johnson, P. H. Krisko, J.-C. Liou, and P. D. Anz-Meador, NASA's new breakup model of EVOLVE 4.0. *Adv. Space Res.*, **28**, 9, 1377-1384 (2001).

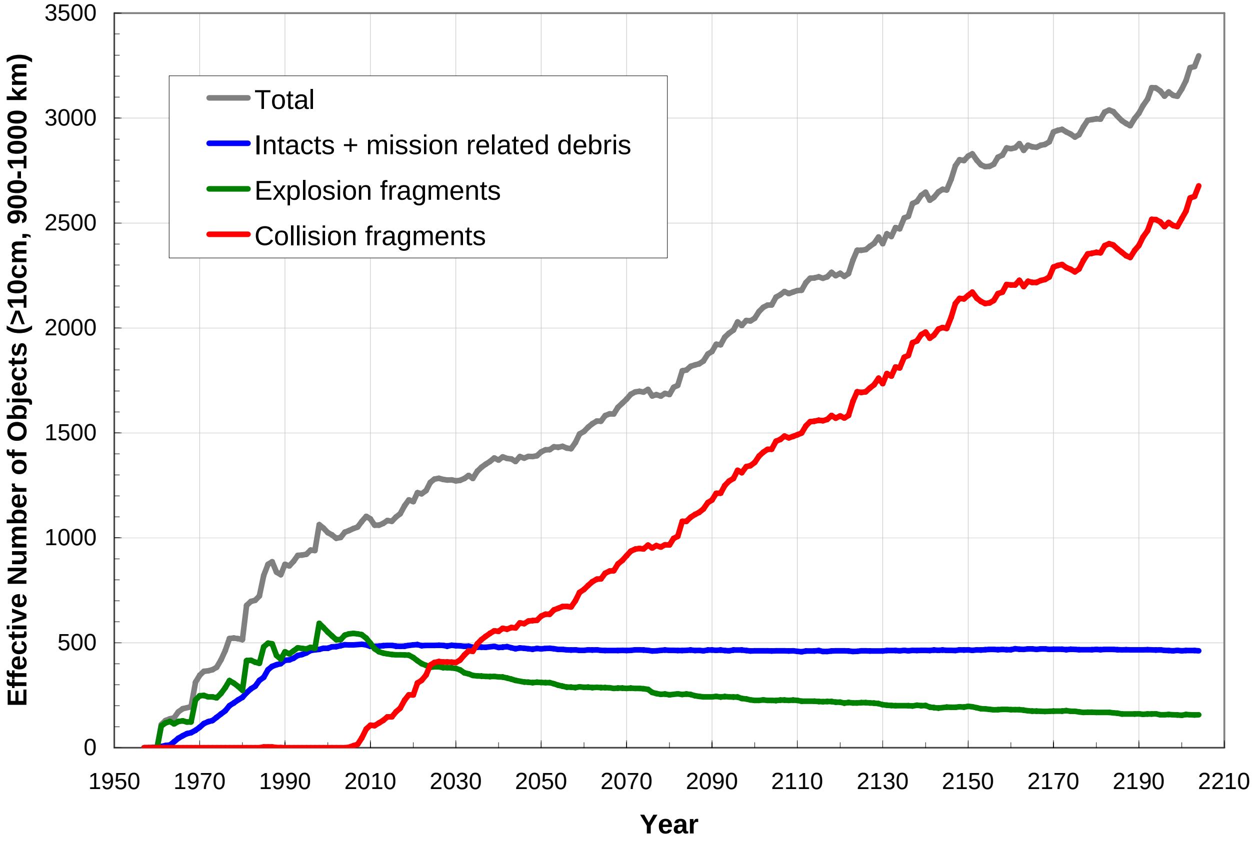
18. Inter-Agency Space Debris Coordination Committee (IADC) members include national space agencies of the United States, the Russian Federation, China, Japan, India, France, Germany, Italy, and the United Kingdom, as well as the European Space Agancy.
19. *IADC Space Debris Mitigation Guidelines*, IADC-02-01, Inter-Agency Space Debris Coordination Committee (2002); electronic copy available at http:www.iadc-online.org.
20. The energy requirements to visit satellites at the same altitude and inclination in different orbital planes can be reduced by maneuvering the remediating vehicle to a different altitude, taking advantage of differential precession of the line of nodes due to the Earth's oblateness, and then returning to the altitude of interest. This concept was described by one of the authors (Johnson) as means for more economically removing nuclear power reactors from Earth orbit [N. L. Johnson, Nuclear Power Supplies in Orbit, *Space Policy*, **2**, 3, 223-233 (1986)]. The amount of propellant savings derived from this technique is dependent upon the time one is willing to wait between remediation operations.



Growth of future debris populations. Effective number of LEO objects, 10 cm and larger, from the LEGEND simulation. The effective number is defined as the fractional time, per orbital period, an object spends between 200 and 2000 km altitudes. Intacts are rocket bodies and spacecraft that have not experienced breakups.



Projected Environment. Spatial density distributions, for objects 10 cm and larger, for three different years. The major increase between 900 and 1000 km altitudes is due to the high collision activities predicted to occur in the same region.



The red zone. Effective number of objects, 10 cm and larger, between 900 and 1000 km altitudes from the LEGEND simulation. The population increase in this region is primarily responsible for the LEO population growth. The large increase in collision fragments forces the total population in this region to increase from the very beginning of the future projection.