Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs

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LIMITING FUTURE COLLISION RISK TO SPACECRAFT

AN ASSESSMENT OF NASA'S METEOROID AND ORBITAL DEBRIS PROGRAMS

Committee for the Assessment of NASA's Orbital Debris Programs

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

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Preface

In 1995, the National Research Council's (NRC's) Committee on Space Debris wrote,

> The threat that orbital debris poses to international space activities is presently not large, but it may be on the verge of becoming significant. If and when it does, the consequences could be very costly—and extremely difficult to reverse. By contrast, the cost of reducing the growth of the hazard can be relatively low. . . . The committee believes that spacefaring nations should take judicious, timely steps now to understand the risk and agree on ways to reduce it.[1]

At that time, no destructive collisions between active spacecraft and debris or meteoroids[2] had been recorded. In addition, the amount of debris in orbit did not include the aftermath of the 2009 Iridium-Cosmos collision and the 2007 on-orbit destruction by the Chinese of a weather satellite as part of an anti-satellite test. Both of those events greatly increased the amount of debris in the near-Earth space environment, thus pushing the threat posed by orbital debris even further toward what was described more than 15 years ago as "on the verge of becoming significant."

In a letter dated April 26, 2010, Bryan O'Connor, NASA's chief of safety and mission assurance, requested that the NRC conduct a study on NASA's meteoroid and orbital debris programs. This letter was a direct response to a request from the White House Office of Management and Budget (OMB) and Office of Science and Technology Policy (OSTP) for NASA to engage in a study of the "opportunities for NASA to enhance the benefits delivered by its orbital debris program in the context of a fairly constrained budget environment." As indicated in the letter, the study's primary task was to review NASA's current efforts with regard to meteoroids and orbital debris and provide recommendations as to whether NASA should increase or decrease its efforts or pursue new directions. The full text of the letter is reprinted as Appendix A of this report, and the specific language of the study charge is contained in Appendix B.

To conduct this study, the NRC's Aeronautics and Space Engineering Board (ASEB) assembled the Committee for the Assessment of NASA's Orbital Debris Programs, composed of 13 experts with a wide range of experience

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[1] National Research Council, *Orbital Debris: A Technical Assessment,* National Academy Press, Washington, D.C., 1995, p. 9.

[2] This report uses the word "meteoroid" according to its precise definition, rather than the term "micrometeoroid," a colloquialism for "small" meteoroids and an imprecise term that does not cover the full range of sizes of meteoroids. However, to avoid adding a new acronym to the literature and to minimize confusion, the committee retains use of the acronym "MMOD" (micrometeoroid and orbital debris) as a modifier (e.g., MMOD programs).

and perspectives. In addition to NASA's orbital debris programs, the committee also evaluated NASA's meteoroid program. Donald Kessler, senior scientist (retired) for orbital debris research at NASA, chaired the committee, which included experts in orbital debris, spacecraft engineering, spacecraft shielding, astrodynamics, meteoroids, hypervelocity impacts, space law, space policy, and risk assessment. Biographical sketches of the committee members are given in Appendix C.

Over the course of the study, the committee met in person four times. During its first meeting on December 13-15, 2010, the committee received overview briefings on many of NASA's relevant programs from the programs' lead researchers and managers. To better understand the context of its charge, the committee met with representatives from OSTP and OMB. In addition, the committee received non-NASA input from sources such as the European Space Agency and the Aerospace Corporation. The committee's second meeting was held January 19-21, 2011, at the NASA Johnson Space Center, where the committee was able to interact directly with many of the NASA researchers and managers who work on orbital debris issues. During the meeting, the committee received more detailed briefings regarding NASA's efforts, particularly those undertaken by NASA's Orbital Debris Program Office.

The committee's third meeting was held March 9-11, 2011, and because of the diversity and number of perspectives and entities involved in space activities, was structured primarily as a public workshop to facilitate hearing from the various stakeholders and interested parties in an efficient manner. On May 26, 2011, the committee released *Summary of the Workshop to Identify Gaps and Possible Directions for NASA's Meteoroid and Orbital Debris Programs,* a short summary report of the workshop that is reprinted in Appendix F. The committee met for the final time on April 25-27, 2011, in order to develop this final report.

The committee notes that several topics of interest related to orbital debris were not included in its statement of task, and as such are not full topics in this report. In particular, the committee was not asked to weigh in on the degree of the threat posed by meteoroids and debris, nor was the committee asked to determine which technology or path is best suited for the removal of debris from orbit. In effect, this study is more a review of NASA's meteoroid and orbital debris programs than an attempt to solve the threat posed by meteoroids and orbital debris.

Although the statement of task refers to a singular NASA program in this field, there are, in fact, numerous program elements spread across NASA mission centers that address MMOD. For the purposes of this report, these elements are referred to as NASA's MMOD programs, although at times they are referred to separately (i.e., meteoroid program, orbital debris programs) depending on the context.

We sincerely thank the experts who made their time available to the committee and provided necessary data, analyses of that data, and insight into technical, management, and political issues. In addition, the NRC staff played an essential role in requesting information, pulling information together, and organizing meetings and editing this report. Without their organizational skills, this document would not have been possible. We would like to particularly thank Paul Jackson, the study director. His commitment to maintaining focus and spending countless hours leading his team, as well as to resolving issues within the committee, made an essential contribution toward increasing the quality of this report.

Donald J. Kessler, *Chair*
George J. Gleghorn, *Vice Chair*
Committee for the Assessment of NASA's
Orbital Debris Programs

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

William Ailor, The Aerospace Corporation,
Ravi B. Deo, EMBR,
Eberhard Grün, Max-Planck-Institut fuer Kernphysik,
John L. Junkins, Texas A&M University,
Charles F. Kennel, Scripps Institution of Oceanography and University of California, San Diego,
Robert Kerr, Scientific Solutions, Inc.,
John M. Klineberg, Space Systems/Loral (retired),
Andrew Piekutowski, University of Dayton Research Institute (retired), and
Michael F. Zedd, Naval Research Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by M. Granger Morgan, Carnegie Mellon University. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

Over the past 50 years, various NASA communities have contributed significantly to maturing NASA's meteoroid and orbital debris (MMOD)[1] programs to their current state. As a result of these community efforts, and to NASA's credit, NASA's MMOD programs and models are now widely used and respected by the providers and users of both government and commercial satellites, nationally as well as internationally. Satellites have been redesigned to protect critical components from MMOD damage by moving critical components from exterior surfaces to deep inside a satellite's structure. Orbits are monitored and altered to minimize the risk of collision with tracked orbital debris. MMOD shielding added to the International Space Station (ISS) protects critical components and astronauts from potentially catastrophic damage that might result from smaller, untracked debris and meteoroid impacts. The space shuttle, as it orbited Earth, and whether docked to the ISS or not, was optimally oriented to protect its fragile thermal protection and thermal radiation systems from MMOD damage. In addition, astronauts inspected its thermal protection system for MMOD damage before the shuttle reentered Earth's atmosphere; Orion, NASA's capsule to carry astronauts to low Earth orbit, includes designs to mitigate the threat of MMOD damage and provide increased safety to the crew.

When a handful of reasonable assumptions are used in NASA's MMOD models, scenarios are uncovered that conclude that the current orbital debris environment has already reached a "tipping point." That is, the amount of debris—in terms of the population of large debris objects, as well as overall mass of debris in orbit—currently in orbit has reached a threshold where it will continually collide with itself, further increasing the population of orbital debris. This increase will lead to corresponding increases in spacecraft failures, which will only create more feedback into the system, increasing the debris population growth rate. The increase thus far has been most rapid in low Earth orbit (LEO), with geosynchronous Earth orbits (GEOs) potentially suffering the same fate, but over a much longer time period. The exact timing and pace of this exponential growth are uncertain, but the serious implications of such a scenario require careful attention because of the strategic importance of U.S. space operations.

The Office of Science and Technology Policy and the Office of Management and Budget contracted with the National Research Council for a study to perform three tasks: review NASA's MMOD programs and efforts, recommend in which of those NASA should increase or decrease its effort or change focus, and determine whether

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[1] This report uses the word "meteoroid" according to its precise definition, rather than the term "micrometeoroid," a colloquialism for "small" meteoroids and an imprecise term that does not cover the full range of sizes of meteoroids. However, to avoid adding a new acronym to the literature and to minimize confusion, the committee retains use of the acronym "MMOD" (micrometeoroid and orbital debris) as a modifier (e.g., MMOD programs).

NASA should pursue work in any new MMOD areas. The official letter requesting the study and the full statement of task for the Committee for the Assessment of NASA's Orbital Debris Programs are in Appendixes A and B, respectively.

REVIEW NASA'S MMOD PROGRAMS AND EFFORTS

As indicated in findings presented throughout this report, the committee identified many positive aspects of NASA's MMOD programs and efforts. Of particular note are the following findings of the committee regarding the resources and responsibilities of NASA's MMOD programs:

> **Finding: NASA's meteoroid and orbital debris programs have used their resources responsibly and have played an increasingly essential role in protecting the safety of both crewed and uncrewed space operations.**
>
> **Finding: The increasing responsibilities given to NASA's meteoroid and orbital debris programs have put pressure on the programs' allotted resources. The increasing scope of work, and the complexity and severity of the debris and meteoroid environment, are outpacing in real dollars the decreasing funding levels of NASA's MMOD programs.**

RECOMMEND CHANGES IN EFFORT OR FOCUS

In its examination of NASA's varied MMOD programs and efforts, the committee found numerous areas in which NASA should consider doing more or different work. Tackling these research areas is likely to enhance the benefits delivered by NASA's MMOD efforts, many of which are listed in Box S.1. Examination of the research needs and management issues listed in Box S.1, along with consideration of the committee's other findings and recommendations, leads to a critical question: How is NASA to prioritize and choose among these numerous research and management areas, given its limited MMOD resources? To address this question, the committee offers the following key, overarching recommendation:

> **Recommendation: NASA should develop a formal strategic plan that provides the basis for prioritizing the allocation of funds and effort over various MMOD program needs. Among the potential research needs and management issues to be considered is the selection listed in Box S.1. The strategic plan should consider short- and long-term objectives, a schedule of benchmark achievements to be accomplished, and priorities among them. Stakeholders should be engaged to help develop and review this plan. Finally, the MMOD strategic plan should be revised and updated at regular intervals.**

Chapter 12 of this report offers the committee's view of what the strategic plan should address. Simply put, the plan must answer four basic questions regarding MMOD: Where are we? Where do we want to go? How are we to get there? and, How do we measure how we are doing?

The committee did not believe that it should prioritize the various areas in which NASA could expand its work; doing so could preempt NASA's following the above recommendation. Given that the committee was told to assume a constrained budget environment, it felt that NASA management would be better suited to prioritize the agency's efforts, in consultation with the broader MMOD scientific community and in response to the committee's various findings and recommendations.

NEW MMOD AREAS FOR NASA TO PURSUE

The study of satellite anomalies, mission-degrading or mission-terminating events affecting on-orbit operational spacecraft, could provide a meaningful data set that would contribute to an increased understanding of the hazards to spacecraft posed by MMOD relative to other hazards. Such a data set would have to be of sufficient fidelity to enable identification of a probable cause of the anomaly. The data set would be strengthened by an

BOX S.1
Research Needs and Management Issues to Be Considered in the Formulation of an MMOD Strategic Plan

Throughout this report, the committee identifies various areas of potential research and a number of management actions that would strengthen NASA's meteoroid and orbital debris (MMOD) programs. Adoption of a strategic plan of the sort envisioned by the committee would require evaluation and prioritization of these areas and activities, which include the following:

1. Perform radar cross-section calibrations using fragments from a large range of materials used in modern satellites and rocket bodies, as well as non-fragmentation debris. (Chapter 2)
2. Expand the environment measurement program to include use of in situ sensors to monitor the flux of debris smaller than a few millimeters. (Chapter 2)
3. Expand efforts to more accurately model sources of debris. (Chapter 3)
4. Develop criteria or a schedule for the regular release of updates to NASA's orbital debris- and meteoroid-related models. (Chapter 3)
5. Establish a base effort to evaluate major environmental uncertainties in three areas: (a) meteoroid velocity distributions, (b) flux of meteoroids of larger sizes (greater than 100 microns), and (c) impact plasma effects. (Chapter 4)
6. Adopt a single model of the meteoroid environment for official use. (Chapter 4)
7. Pursue improving the understanding of the hazards posed by interplanetary meteoroids. (Chapter 4)
8. Expand research on meteoroids to include an understanding of the possible link between spacecraft electrical anomalies and major meteor showers. (Chapter 4)
9. Perform a broad integrative analysis of the various risks posed by meteoroids and orbital debris (whether probabilistic risk analysis or some alternative). (Chapter 5)
10. Identify major areas of uncertainty in current environmental models and risk assessments, and develop test plans and analyses to reduce that uncertainty. (Chapter 5)
11. Undertake an effort to refine models for predicting impact damage using a statistics-based approach. (Chapter 6)
12. Undertake an effort to re-derive the ballistic limit equations in the BUMPER code using a statistics-based approach that would provide information regarding uncertainty bounds and/or confidence intervals. (Chapter 6)
13. Increase efforts to characterize the damage resulting from impacts of orbital debris of various particle shapes and densities. (Chapter 6)
14. Expand program plans to include the technology, political, and legal considerations necessary to increase international cooperation on mitigation and remediation measures to stabilize the orbital debris environment. (Chapter 7)
15. In regard to reentry risks, re-examine how thresholds for ground injury effects are estimated and provide confidence bounds and uncertainty assessments. (Chapter 8)
16. Develop a research plan for (a) assessing the impact of the inaccuracy in the uncertainty in computing the probability of collision and in the ensuing risk assessment and (b) improving the accuracy of the computation of the probability of collision in the presence of these uncertainty errors. (Chapter 9)
17. Initiate an effort to record, analyze, report, and share data on satellite anomalies in order to better quantify the risk from orbital debris particulates too small to be cataloged yet large enough to disrupt space operations. (Chapter 10)
18. Continue to engage the private sector, U.S. federal agencies, and international agencies in developing cooperation and political will to effectively address issues regarding orbital debris. (Chapter 11)
19. Identify budget requirements and areas of responsibilities, including personnel and a single point of contact, for maintaining a viable program as budgets and personnel change. (Chapter 12)
20. Schedule periodic technical assessments written for policy makers and stakeholders. (Chapter 12)
21. Continue to emphasize the long-term objectives of the MMOD programs through public discussions and improved long-term models. (Chapter 13)
22. Monitor and inventory the costs of debris avoidance, mitigation, surveillance, and reporting over time. (Chapter 13)

increased in situ MMOD environment measurements program, similar to that conducted to measure the meteoroid environment prior to the Apollo program.

> **Recommendation: NASA should initiate a new effort to record, analyze, report, and share data on spacecraft anomalies in order to better quantify the risk from particulates too small to be cataloged yet large enough to disrupt spacecraft operations. The results of this effort would provide general insights into the effects of meteoroids and orbital debris on operational space systems. Eventually, this effort could provide data to upgrade current MMOD models—the Meteoroid Environment Model, Orbital Debris Environment Model, and BUMPER.**

The committee also recommends expansion of existing efforts in a number of areas to more adequately measure and model the MMOD environment and effectively minimize the risk to spacecraft and astronauts—both by designing spacecraft to survive the MMOD environment, and by implementing policies to limit or reverse growth in the population of orbital debris. The recommendations include both technical and policy issues. Most of the technical issues can be addressed with existing technology. Although the committee found no lack of technical capability within NASA's MMOD community, most of that capability is only "one deep" and could quickly disappear as the MMOD programs age.

> **Finding: Nearly all of NASA's MMOD programs are only one person deep in staffing. This shortage of staffing makes the programs highly vulnerable to budget reductions or changes in personnel. Further reductions in real budgetary support over the coming years could threaten the viability and scope of ongoing MMOD programs.**

New resources will be required if NASA is to pursue the 2010 National Space Policy goals of "research and development of technologies and techniques . . . to mitigate and remove on-orbit debris."[2] Political and legal issues will also have to be addressed. If the technologies to remove on-orbit debris are developed and implemented, the management requirements on NASA as an agency may become as significant as those associated with any major NASA program.

If the United States is to pursue debris removal operations, then extensive international cooperation will be required, particularly because current international legal principles restrict nations to retrieving or otherwise salvaging only their own objects, and around 30 percent of the objects are attributable to the United States.

> **Finding: Debris removal activity that involves selecting and removing any given object—debris or otherwise—from space, crosses crucial national and international legal thresholds.**

> **Recommendation: NASA's meteoroid and orbital debris programs should engage the NASA General Counsel's Office and, through that office, the U.S. State Department regarding the legal requirements and diplomatic aspects of active debris removal.**

It is likely that changes in NASA's current management structure will be necessary to address MMOD funding and policy issues if the MMOD programs are to continue to be a national resource and maintain their international leadership. Such changes will contribute to preserving the existing capabilities of the MMOD programs, and also will allow them to expand in a more cost-effective approach to minimizing future risk.

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[2] *National Space Policy of the United States of America*, June 28, 2010, p. 7, available at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf, accessed July 6, 2011.

Finding: NASA's management structure has not kept pace with the expanding responsibilities of its MMOD programs. Consequently, the MMOD programs do not have a single management and budget point that can efficiently coordinate all of the current and planned activities and establish clear priorities.

Recommendation: NASA should review the current management structure of its MMOD programs in order to achieve better coordination, provide improved central decision making, and establish a framework for setting priorities. This framework should include a major interface with Congress, other federal and state agencies, and the public.

LOOKING TO THE FUTURE

The danger posed by meteoroids and orbital debris is fundamentally a long-term environmental issue and should be addressed as such. Mitigation alone has proven to be insufficient, with the current environment in LEO representing an increasing hazard to spacecraft and astronauts there. Although current mitigation practices in other regions of Earth orbit may limit the MMOD hazard in the short term, a time will eventually come when those regions will likely become more hazardous as LEO has. Consequently, the sooner NASA acts to ensure effective long-term mitigation at all altitudes, the less drastic or expensive future actions may be. Such planning will require an integrated effort involving all levels of management and policy makers, as well as adequate support at the technical levels.

Recommendation: NASA should lead public discussion of the space debris problem to emphasize debris as a long-term concern for society that must continue to be addressed today. Necessary steps include improvements in long-term modeling, better measurements, more regular updates of the debris environmental models, and other actions to better characterize the long-term evolution of the debris environment.

1

Introduction and Historical Background

ORBITAL DEBRIS AND RELATED EFFORTS

NASA's orbital debris program officially began in 1979. Lacking an official program designation at the time, it was initiated in the Space Sciences Branch at Johnson Space Center (JSC) as a result of research that concluded that impacts from Earth orbital debris had the potential to become a greater hazard to spacecraft than the natural meteoroid environment. At that time, there were no measurements of the debris environment for objects smaller than about 10 cm—the smallest size of an object in the catalog maintained by the North American Aerospace Defense Command (NORAD).[1] However, there was much more than sufficient mass in orbit to produce a significant debris population in the less-than-10-cm-size range. The inevitable mechanism for creating such small debris was collisions between the more massive, cataloged objects. In 1978, this mechanism was predicted to become important around the year 2000, depending on the growth in the cataloged debris population. However, other mechanisms (such as explosions in orbit) were also capable of producing a significant uncataloged population of debris, and could have already done so.[2]

The NASA orbital debris program began at JSC with a very small budget of $70,000[3] provided by the NASA Headquarters Advanced Program Office with the initial goals of characterizing the hazard to spacecraft and recommending mitigation standards that would minimize the growth of the orbital debris environment.[4] During the program's first few years it quickly established—by examining returned spacecraft surfaces and using ground telescopes—that the hazard from debris smaller than about 1 cm had already exceeded the meteoroid hazard in some altitudes below 2,000 km. The funding for the program grew as it added the goal of providing support to other NASA programs as well as to other agencies, both national and international, and as it established a debris measurements program using shorter-wavelength radars. Hypervelocity gun facilities were reconstructed, after having been dismantled more than a decade earlier, for the purpose of developing new shielding concepts for the space station. By 1990, the program had established a debris monitoring program, which included sampling the low Earth orbit (LEO) environment for debris of sizes as small as 6 mm using the Haystack X-band ground

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[1] The North American Aerospace Defense Command (NORAD) no longer maintains the official catalog of meteoroids; it is currently the responsibility of the U.S. Strategic Command.

[2] D.J. Kessler and B.G. Cour-Palais, Collision frequency of artificial satellites: The creation of a debris belt, *Journal of Geophysical Research* 83(A6):2637-2646, 1978.

[3] All dollar figures in this report are for then-year dollars.

[4] D.S.F. Portree and J.P. Loftus, *Orbital Debris: A Chronology,* NASA/TP-1999-208856, NASA, Washington, D.C., January 1999.

radar. The examination of all spacecraft surfaces returned from space, including all space shuttles, resulted in the identification of impacts on these surfaces from both meteoroids and orbital debris.[5] NASA and the Department of Defense (DOD) established a working group, sharing resources and information,[6] and beginning in 1992, NASA worked with DOD to use a series of hypervelocity tests conducted by DOD to characterize the fragments produced from collisions in orbit.[7] DOD's meteoroid and orbital debris (MMOD) efforts and the responsible parties are described in Box 1.1.

In its early stages the NASA program developed education programs and organized workshops in order to share information from other groups. When it became evident that upper-stage rocket explosions were a major debris producer, bilateral meetings began between NASA and the European Space Agency (ESA) in 1987. By 1991, NASA had also met with space agencies in the USSR, Japan, and China, where each major space agency quickly and informally agreed to the concept of operational procedures for minimizing the possibility of future explosions in orbit.[8] These multilateral meetings led to the formal establishment of the Inter-Agency Space Debris Coordination Committee (IADC), under which each major space agency reaffirmed its agreement to these operational procedural concepts that minimize the possibility of future explosions in orbit. NASA also participated in national and international scientific conferences such as those sponsored by the Committee on Space Research (COSPAR), the International Astronautical Federation (IAF), the American Institute of Aeronautics and Astronautics (AIAA), and the American Astronautical Society (AAS), which led to sessions at those conferences devoted totally to orbital debris studies.

The orbital debris program became a major contributor to the design of a safer International Space Station (ISS)[9] and supported the space shuttle[10] program to bring it up to the safety standards of the ISS. NASA also supported DOD operations so that certain tests could be safely conducted in space. By 1995, the NASA program had established a comprehensive set of mitigation guidelines. Although these guidelines applied only to NASA programs, they were shared with other national and international agencies for their consideration.

Since the mid-1990s, those mitigation guidelines have been accepted not only by NASA, but also by other U.S. and international agencies.[11] Membership in the IADC increased and has contributed to a major exchange of data when the IADC meets annually. Other countries now have their own environment models, observation programs, and hypervelocity testing programs. At the recommendation of the IADC, the United Nations has now adopted the intent of the NASA guidelines.[12]

Beginning in the late 1990s, the orbital debris program began to expand into several programs that are today collectively referred to as "NASA's MMOD programs." The activities of environment definition and debris mitigation became the Orbital Debris Program Office (ODPO) at JSC. Spacecraft shielding and the examination of returned spacecraft surfaces are organized under what is known as the Hypervelocity Impact Technology Facility (HITF; at JSC). The Meteoroid Environment Office (MEO) was formed at Marshall Space Flight Center (MSFC) in 2004 (see the section "Meteoroids" below). Early work to come up with a probabilistic approach to active avoidance of collision with cataloged debris grew into operational activities for the ISS; that approach has grown into

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[5] National Research Council, *Orbital Debris: A Technical Assessment*, National Academy Press, Washington, D.C., 1995.

[6] National Science and Technology Council Committee on Transportation Research and Development, *Interagency Report on Orbital Debris*, Office of Science and Technology Policy, Washington, D.C., November 1995, available at http://orbitaldebris.jsc.nasa.gov/library/IAR_95_Document.pdf, accessed July 6, 2011.

[7] D.M. Hogg, T.M Cunningham, and W.M. Isbell, *Final Report on the SOCIT Series of Hypervelocity Impact Tests,* Report No. WL-TR-93-7025, Wright Laboratory, Armament Directorate, Wright-Patterson Air Force Base**,** Ohio, July 1993.

[8] Inter-Agency Space Debris Coordination Committee, *Terms of Reference for the Inter-Agency Space Debris Coordination Committee (IADC),* IADC-93-01, October 4, 2006, available at http://www.iadc-online.org/index.cgi?item=torp_pdf, accessed July 6, 2011.

[9] National Research Council, *Protecting the Space Station from Meteoroids and Orbital Debris,* The National Academies Press, Washington, D.C., 1997, available at http://www.nap.edu/catalog.php?record_id=5532.

[10] National Research Council, *Protecting the Space Station from Meteoroids and Orbital Debris,* 1997.

[11] Inter-Agency Space Debris Coordination Committee, *Space Debris Mitigation Guidelines*, IADC-02-01, revision 1, September 2007, available at http://www.iadc-online.org/index.cgi?item=docs_pub.

[12] United Nations Office for Outer Space Affairs, *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space,* United Nations, New York, N.Y., 2010, available at http://orbitaldebris.jsc.nasa.gov/library/Space%20Debris%20Mitigation%20Guidelines_COPUOS.pdf.

BOX 1.1
U.S. Government Entities Responsible for Orbital Debris

The Committee for the Assessment of NASA's Orbital Debris Programs was tasked with evaluating NASA's meteoroid and orbital debris (MMOD)-related efforts but acknowledges that NASA is not the sole organization involved in addressing the problem of orbital debris and meteoroids. The other primary U.S. government actors working on MMOD issues include numerous Department of Defense (DOD) groups, primarily within the U.S. Strategic Command (USSTRATCOM) and the Air Force Space Command (AFSPC):

- *USSTRATCOM:* Headquartered at Offutt Air Force Base near Omaha, Nebraska, and one of ten unified commands in the DOD, USSTRATCOM is responsible for the nation's nuclear command, space operations, global strike, DOD information operations, and global missile defense, among other duties.[1]
  - *The Joint Space Operations Center (JSpOC):* Within USSTRATCOM, JSpOC is in charge of detecting, tracking, and identifying man-made objects in Earth orbit.[2] When an object can be identified with a particular launch but is not a classified military satellite, it appears in the U.S. Space Surveillance Network's (SSN's) publicly available catalog (see below), which lists more than 16,000 cataloged objects in Earth orbit.[3] However, a total of about 22,000 objects are being tracked routinely and their orbits are being recorded.[4]
  - *The U.S. Space Surveillance Network:* Operated under the aegis of USSTRATCOM, the SSN consists of a global network of radar and optical sensors belonging to all branches of the U.S. military. The SSN compiles and updates the primary orbital debris catalog used by the federal government.
- *AFSPC:* A large organization within the Air Force that is spread across 88 locations worldwide, AFSPC is responsible for space launch operations at launch bases on the East and West Coasts, and its many other responsibilities include conducting and maintaining cyberspace operations. AFSPC provides services, facilities, and range safety control for all DOD, NASA, and commercial launches and also integrates and coordinates command and control of all DOD satellites among operators.[5]

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[1] See the USSTRATCOM website, available at http://www.stratcom.mil/about/, accessed July 21, 2011.

[2] U.S. Strategic Command, "USSTRATCOM Space Control and Space Surveillance," available at http://www.stratcom.mil/factsheets/USSTRATCOM_Space_Control_and_Space_Surveillance, accessed July 21, 2011.

[3] As of July 6, 2011, there were 16,094 objects in the Space Surveillance Network's public catalog. See J.-C. Liou, ed., Satellite box score, *Orbital Debris Quarterly News* 15(3):10, July 2011, available at http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv15i3.pdf, accessed July 21, 2011.

[4] U.S. Strategic Command, "USSTRATCOM Space Control and Space Surveillance," available at http://www.stratcom.mil/factsheets/USSTRATCOM_Space_Control_and_Space_Surveillance, accessed July 21, 2011.

[5] U.S. Air Force, "Fact Sheet: Air Force Space Command," November 2010, available at http://www.afspc.af.mil/library/factsheets/factsheet_print.asp?fsID=3649&page=1, accessed July 21, 2011.

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what is called Conjunction Assessment Risk Analysis (CARA). In 2005, the Goddard Space Flight Center (GSFC) began using CARA to provide collision avoidance information for operational uncrewed spacecraft. Launch Collision Avoidance (COLA), administered at the Kennedy Space Center (KSC), grew out of range safety concerns and screens against possible conjunctions with known objects in orbit, but only during the launch phase of a mission. Although these other meteoroid and orbital debris programs (HITF, MEO, and CARA/COLA) are not officially part of the ODPO, there is close coordination between them.

In 1993, the responsibilities of the ODPO were expanded to include minimizing the hazard on the ground from reentering debris and providing short-term operational support to both crewed and uncrewed spacecraft in the form of warnings that may result in collision avoidance maneuvers or delays in launch in order to avoid a potential hazard.[13] For example, the ODPO provided support for the U.S. presidential decision to destroy the USA-193 satellite in February 2008 by evaluating the potential hazard to civilians on the ground from USA-193's toxic hydrazine fuel and tank, as well as ensuring that the hazard to operational spacecraft was minimal (see Box 1.2).[14] The ODPO now provides warning after any unplanned breakups of spacecraft in orbit using the Satellite Breakup Assessment Model (SBRAM), predicting regions of space to avoid, if possible. Such predictions are essential to the timing of certain DOD operations involving tests that may produce a temporary region of higher risk, for which NASA provides support.

NASA is also now providing CARA for uncrewed spacecraft, whereby spacecraft with the capability to maneuver are warned of the risk of a collision with other cataloged objects and given the option to maneuver. Beginning in 2002, NASA's research and engineering orbital debris models were reformatted to more easily include the most recent data and to allow for greater flexibility in determining the most efficient mitigation and remedial actions.

As of 1995, key NASA models, measurements, and testing results were combined into a single suite of models (with a graphic user interface) that is publicly available. Known as the Debris Assessment Software (DAS), this application allows any spacecraft designer to determine if a spacecraft is meeting NASA's current mitigation guidelines, as well as whether critical systems on the spacecraft have a level of protective shielding that is acceptable to the spacecraft designer.

Figure 1.1 illustrates how NASA's measurements, modeling, and test programs combine to provide a set of customer-user tools and services, as well as research tools used to recommend mitigation and remediation options toward minimizing growth in the orbital debris population. Many of these models have undergone nearly constant upgrades since the beginning of the program, whereas others represent newly developed operational tools. The models and various components of Figure 1.1 are described in more detail in the appropriate chapters of this report.

One of NASA's major mitigation standards has been that "maneuverable spacecraft that are terminating their operational phases at altitudes of less than 2,000 km above Earth shall be maneuvered to reduce their orbital lifetime, commensurate with 25-year low-Earth orbit lifetime limitations."[15] The reason for this 25-year rule[16] was that it has been recognized since the beginning of the program that an increasing accumulation of non-operational spacecraft and upper stages would inevitably lead to increasing collisions involving those objects and would become the major source of small debris. NASA's goal was to gain both national and international acceptance of the 25-year rule.

Yet although the orbital debris mitigation guidelines developed by NASA were gaining wider acceptance by the space community, an increasing number of studies, both national and international, were coming to the conclusion that even absolute compliance with the 25-year rule would be insufficient to prevent the debris population present below 2,000 km (LEO) from continuing to increase as a result of random collisions involving non-operational intact debris.[17] These studies concluded that the rate of collisions had already reached the point that debris would

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[13] NASA, *Process for Limiting Orbital Debris,* NASA-STD 8719.14 (Change 4), NASA, Washington, D.C., September 2009, available at http://www.hq.nasa.gov/office/codeq/doctree/871914.pdf.

[14] J. Oberg, U.S. satellite shootdown: The inside story, *IEEE Spectrum*, August 2008, available at http://spectrum.ieee.org/aerospace/satellites/us-satellite-shootdown-the-inside-story.

[15] Requirement 56876 of NASA Procedural Requirements 8715.6A. See http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_8715_006A_&page_name=Chapter3.

[16] The "25-year rule" is a guideline adopted by the international Inter-Agency Space Debris Coordination Committee (IADC) in its "IADC Space Debris Mitigation Guidelines" released in 2002 and revised in 2007. The "rule" encourages entities with objects in low Earth orbit to ensure that their spacecraft and/or launch hardware are in an orbit that will decay and cause said object to reenter Earth's atmosphere within 25 years to mitigate the creation of more orbital debris. See http://www.iadc-online.org/Documents/Docu/IADC_ Mitigation_Guidelines_Rev1_Sep07.pdf.

[17] D.J. Kessler, Collisional cascading: The limits of population growth in low Earth orbit*, Advances in Space Research* 11(12):63-66, 1991; S.-Y. Su, On runaway conditions of orbital debris environment, *Advances in Space Research* 13(8):221-224, 1993; A. Rossi, A. Cordelli, P. Farinella, and L. Anselmo, Collisional evolution of the Earth's orbital debris cloud, *Journal of Geophysical Research—Planets* 99(E11):23195-23210, 1994; L. Anselmo, A. Cordelli, P. Farinella, C. Pardini, and A. Rossi, *Modelling the Evolution of the Space Debris Population: Recent Research Work in Pisa*, ESA SP-393, European Space Operations Centre, European Space Agency, Darmstadt, Germany, 1997, pp. 339-344; D.J. Kessler, *Critical Density of Spacecraft in Low Earth Orbit Using Fragmentation Data to Evaluate the Stability of the Orbital Debris Environment,* Report LMSEAT-3393, Lockheed Martin, February 2000; P.H. Krisko, J.N. Opiela, and D.J. Kessler, *The Critical Density Theory in LEO as Analyzed by EVOLVE 4.0,* ESA SP-473, European Space Operations Centre, European Space Agency, Darmstadt, Germany, 2001, pp. 273-278; J.-C. Liou and N.L. Johnson, Risks in space from orbital debris, *Science* 311:340-341, 2006.

BOX 1.2
2007 Chinese Anti-Satellite Mission Test and 2008 U.S. Destruction of USA-193

As of December 27, 2006, the U.S. Space Surveillance Network (SSN) was tracking 9,949 cataloged objects larger than 10 cm. On January 11, 2007, China conducted a direct-ascent anti-satellite (ASAT) missile test with its FENGYUN 1C polar-orbiting weather satellite as the target. The destruction of the satellite created more than 3,000 trackable objects and an estimated 150,000 debris particles larger than 1 cm, making it the largest debris-generating event in the history of man-made orbital debris, increasing the known existing orbital debris population in 2007 by more than 15 percent.[1,2] For comparison, the previous largest orbital debris-generating event, the explosion of a U.S. Pegasus rocket body in 1996, created 713 trackable pieces of debris. On June 22, 2007, NASA was forced to maneuver its Terra satellite to avoid debris from China's ASAT test.

Two years after the destruction of China's satellite, only 50 pieces of debris had decayed from orbit.[3] As of May 2011, the SSN had cataloged 3,118 trackable pieces of debris (approximately 10 cm in diameter or larger) still in orbit from China's ASAT test, constituting nearly 20 percent of the entire debris population of particles 10 cm or larger currently being tracked in the SSN's public catalog, which was at 16,094 as of July 6, 2011.[4,5] Based on models from the Center for Space Standards and Innovation (CSSI), the remnants of FENGYUN 1C will likely remain in orbit for at least a century.

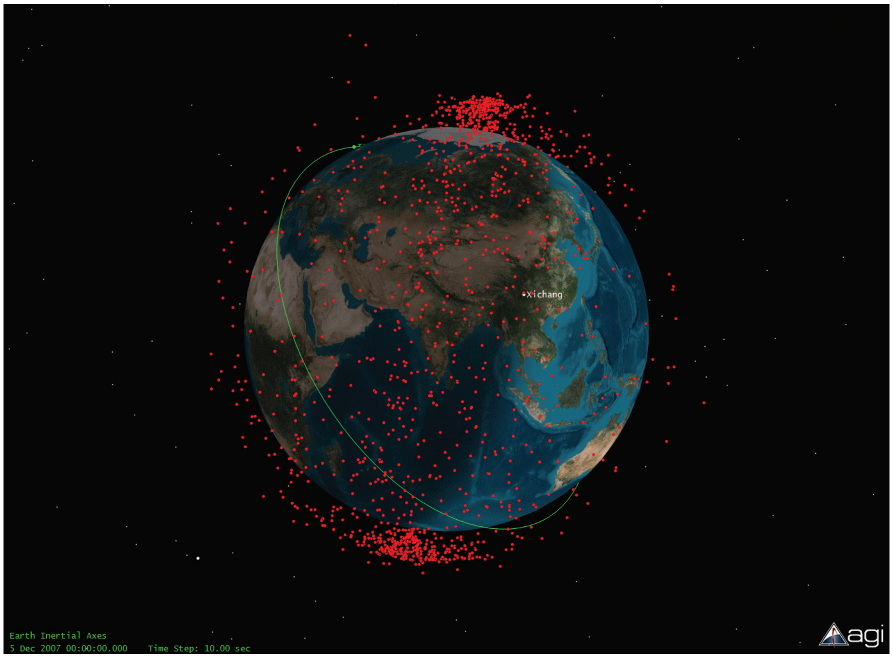

FIGURE 1.2.1 The International Space Station's orbit (*green*) and the debris ring (*red*) from the Chinese ASAT test (December 5, 2007). SOURCE: Courtesy of Dr. T.S. Kelso, CelesTrak.com.

On February 21, 2007, the United States successfully destroyed its National Reconnaissance Office-operated USA-193 satellite, because it posed a serious threat to Earth. The purpose of this missile intercept was to break up the spacecraft and, more specifically, its thick metal fuel tank, which was nearly three-quarters full of toxic hydrazine propellant used for maneuvering the satellite while in orbit.[6] Because USA-193 failed shortly after reaching orbit, its fuel would never be depleted through normal operational use.

continued

BOX 1.2 Continued

The Department of Defense and NASA had run tests that determined that the hydrazine tank would survive atmospheric entry intact and thus pose a risk of casualties from dispersal of the deadly hydrazine fuel.

Unlike the Chinese FENGYUN 1C satellite remnants, debris from USA-193 reentered Earth's atmosphere within 4 months of the satellite's destruction.[7]

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[1] NASA, *Orbital Debris Quarterly News,* Volume 12, Issue 1, January 2008.

[2] NASA, *Orbital Debris Quarterly News,* Volume 11, Issue 2, April 2007.

[3] Ibid.

[4] See http://celestrak.com/events/asat.asp.

[5] NASA, *Orbital Debris Quarterly News,* Volume 15, Issue 3, July 2011, p. 10.

[6] G.J. Gilmore, Navy missile likely hit fuel tank on disabled satellite, *American Forces Press Service,* February 21, 2008, available at http://www.defense.gov/news/newsarticle.aspx?id=49030.

[7] See http://celestrak.com/events/usa-193.asp.

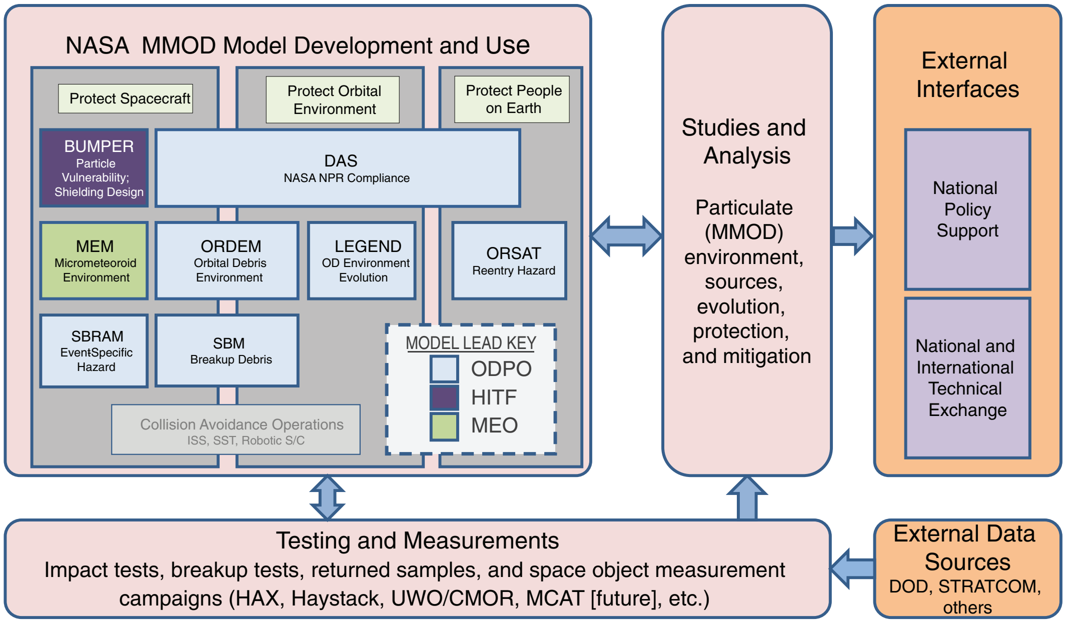

FIGURE 1.1 A depiction of the flow of information between various organizational elements of NASA's MMOD programs, showing vital aspects of the programs as they relate to both internal and external customers. MMOD models are developed to contribute to studies and analyses that support not only internal missions but also a significant number of interagency deliberations within the United States and meaningful dialogs internationally. Developed by NASA's Orbital Debris and Program Office, Hypervelocity Impact Test Facility, and Meteoroid Environment Office, the models developed focus on protecting spacecraft, the environment, and people on Earth. Development and use of the models are supported by a robust testing and measurement program that is routinely augmented by external sources of data.

be generated faster than it could be removed by natural forces, mainly atmospheric drag. According to NASA's most updated long-term model, it would be necessary to remove five large, intact objects per year over the next 100 years in order to prevent this future growth in the orbital debris population, assuming that 90 percent of future launches follow NASA's current mitigation guidelines, including that no further explosions or other major releases of debris occur. However, the most important guideline is international compliance with the 25-year rule. If these guidelines are not followed, the number of intact objects to be removed could become much higher.[18]

These conclusions were reinforced by China's anti-satellite test in January 2007, which involved an intentional collision with its own weather satellite at an altitude of 865 km (see Box 1.2), and then in February 2009 by the accidental collision between the Cosmos 2251 and Iridium 33 satellites at an altitude of 789 km. These two collisions essentially negated the consequences of more than 20 years of international compliance to guidelines that prevented upper rockets from continuing to explode in orbit. As illustrated in Figure 1.2, following these two events, the amount of cataloged fragmentation debris in orbit more than doubled, after having remained nearly constant for more than 20 years.[19] In addition, NASA's Haystack radar observation program measured a significant increase in the 1-cm-debris environment at all altitudes below 1,000 km after China's 2007 test.[20] After the Cosmos–Iridium collision, both the Haystack and Goldstone radars observed a significant increase in the debris population down to sizes as small as 2 mm, consistent with model predictions for collisions involving intact payloads.[21]

The Cosmos–Iridium conjunction was actually the fourth confirmed accidental collision between cataloged objects, all at altitudes between 680 km and 980 km. The first three occurred between 1991 and 2005, produced less than four cataloged fragments each, and did not draw much attention—so little attention that the 1991 collision was not recognized until 2005. NASA's findings that if mitigation standards are followed perhaps only five large objects per year might have to be removed from orbit in order to stabilize the orbital debris environment, plus concern over the amount of debris that these two collision events created, have increased interest in strengthening NASA's mitigation standards and researching the options for remediation.

In 2010, the new National Space Policy expanded NASA's role in the orbital debris program further with the goal of "improved information collection and sharing for space object collision avoidance; protection of critical space systems and supporting infrastructures, with special attention to the critical interdependence of space and information systems; and strengthening measures to mitigate orbital debris." The policy also directs NASA and DOD to "pursue research and development of technologies and techniques . . . to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment."[22] Along with these expanded roles comes a need for additional resources, yet funding levels for the programs have not increased commensurate with their increased responsibilities. The ODPO "procurement funding" (no civil servant salaries or travel) has been constant at $3 million per year for the past 15 years, except for the years 2002 and 2003, when it was cut in half; this overall level represents a significant decrease when adjusted for inflation. As a result, capability has been lost and analysis efforts delayed. For example, during 2002 and 2003, the office permanently terminated operations of its Orbital Debris Observatory located in Cloudcroft, New Mexico, shut down the ODPO website for 2 years, and delayed model upgrades that would include debris shape, definition of the debris population at low inclinations, modeling of solid rocket motor aluminum oxide ejecta, and studies to assess the long-term environmental impact of various mitigation measures. Many of these modeling efforts have yet to be accomplished. In addition to these losses and delays, the 2010 National Space Policy's requirements for increased effort from NASA's orbital debris program will only stress resources further.

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[18] J.-C. Liou, N.L. Johnson, and N.M. Hill, Controlling the growth of future LEO debris populations with active debris removal, *Acta Astronautica* 66(5-6):648-653, 2010.

[19] D.J. Kessler, J.-C. Liou, N.L. Johnson, and M. Matney, The Kessler syndrome: Implications to future space operations, *Advances in the Astronautical Sciences* 137:47-61, 2010.

[20] M. Horstman, Q. Juarez, V. Papanyan, E. Stansbery, and C. Stokely, Measurements of the orbital debris environment by the Haystack and HAX radars during fiscal year 2007, *Orbital Debris Quarterly News* 14(3):3-4, 2010, available at http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv14i3.pdf.

[21] M. Matney, Small debris observations from the Iridium33/Cosmos 2251 collision, *Orbital Debris Quarterly News* 14(2):6-8, 2010, available at http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ ODQNv14i2.pdf.

[22] *National Space Policy of the United States of America*, June 28, 2010, p. 7, available at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.

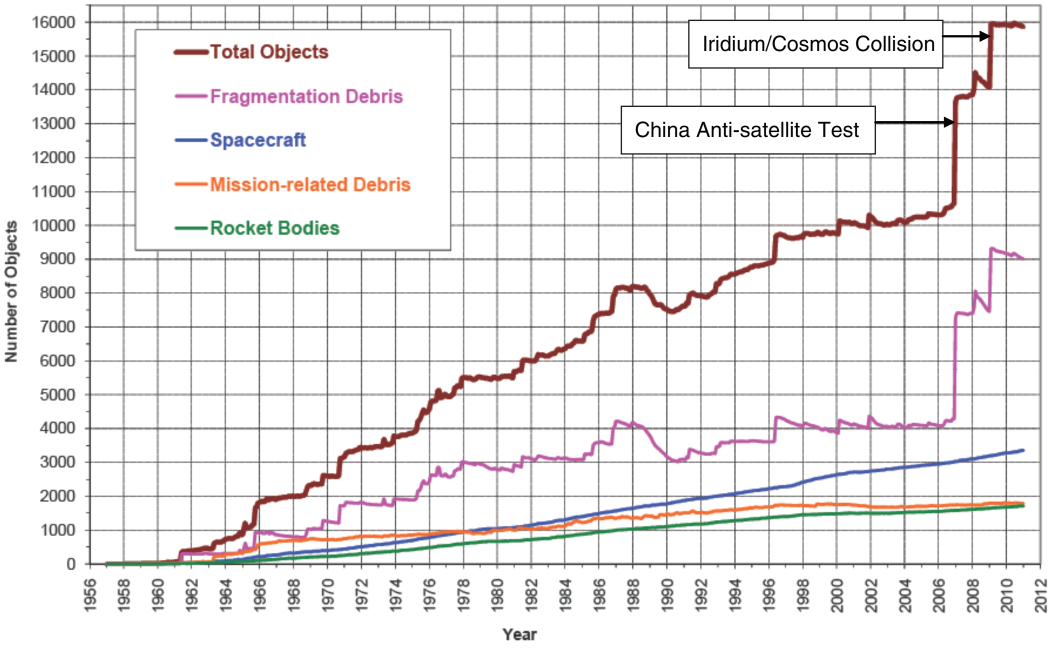

FIGURE 1.2 Monthly number of objects by type in Earth orbit as officially cataloged by the U.S. Space Network. "Fragmentation debris" includes satellite breakup debris and anomalous-event debris; "mission-related debris" includes all objects dispensed, separated, or released as part of a planned mission. After having been nearly constant since 1987, fragmentation debris jumped from 4,000 objects in 2007 to 9,000 in 2009 as a result of two collisions in LEO. SOURCE: Courtesy of NASA, "Monthly Number of Objects in Earth Orbit by Object Type," *Orbital Debris Quarterly News*, Vol. 15, Issue 1, NASA, January 2011, p. 10.

The committee heard from a number of speakers representing other U.S. agencies, as well as commercial space industries and the international community. Without exception, all speakers complimented NASA's Orbital Debris Program Office for its leadership and working relationship with the community. Some went so far as to say that the program was essential to their operations.

METEOROIDS AND RELATED ACTIVITIES

The NASA meteoroid program began with the start of the space program, 50 years ago. At that time, JSC, MSFC, Ames Research Center, GSFC, and Langley Research Center each had its own, nearly independent, meteoroid program.[23] The goal of these programs was to characterize the hazard of meteoroids to spacecraft, especially crewed spacecraft. Meteors were measured both from optical cameras and by radar from the ground. A large number of spacecraft experiments were flown during the 1960s to measure the environment, and the surfaces of these returned spacecraft, such as the windows from crewed spacecraft, were examined for impacts.[24] Samples of interplanetary dust particles in the stratosphere were also collected to better understand the sources and characteristics of meteoroids. Some of these experiments and samples were misinterpreted as indicating a high meteoroid flux (i.e., the number of objects impacting or passing through a unit area per unit time). However, by 1970 it was

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[23] D.J. Kessler, "A Partial History of Orbital Debris: A Personal View," presentation at the Hypervelocity Shielding Workshop, Institute for Advanced Technology, Galveston, Tex., March 8-11, 1998, pp. 81-89.

[24] H.A. Zook, R.E. Flaherty, and D.J. Kessler, Meteoroid impacts on the Gemini windows, *Planetary and Space Sciences* 18(7):953-964, July 1970.

believed that the near-Earth meteoroid hazard was sufficiently understood and benign, and so all of these programs were either significantly reduced or eliminated; this culminated in the issuance of near-Earth[25] and interplanetary meteoroid environment[26] models that were still being used by NASA and other agencies through most of the 1990s. Some meteoroid studies continued, but studies in the United States had the goal of understanding the history of the evolution of comets, asteroids, and the solar system, and studies with the goal of understanding the hazard to spacecraft mostly shifted to other countries. Some of the NASA meteoroid models still in use today for the design of spacecraft are based entirely on data collected and analysis conducted prior to 1970.[27]

However, on July 27, 1993, NASA received a wake-up call when a reporter asked how NASA planned to handle the Perseid meteor storm on August 12, 1993, while the space shuttle was in orbit. NASA had been completely unaware of the predicted meteor storm and had no answer. Any predictions that could be obtained in the time available proved to be too uncertain, and so the launch was postponed until after the storm.[28] Many uncrewed spacecraft were reoriented to protect their more critical surfaces, the first time operational changes occurred to spacecraft as a direct result of predictions relating to short-term changes in the meteoroid environment. Since this incident in 1993, the meteoroid program has slowly grown, at first to better understand meteor storm predictions (particularly those of the Leonids from 1998 to 2002), and later to understand other areas of uncertainty in the meteoroid environment.

In near-Earth space, the meteoroid hazard is still larger than the orbital debris hazard for any spacecraft operating above an altitude of 2,000 km. Prior to 1970, NASA was also concerned with defining the interplanetary meteoroid environment. However, with very little data to support them, the interplanetary models produced at that time sometimes involved assuming unknown sources and extrapolating the known sources of comets and asteroids over many orders of magnitudes. As a result, those early models had large uncertainties. The situation is not much better today, given that some of those same assumptions are still being used, but NASA has begun planning crewed missions that extend into interplanetary space.

The scientific community outside NASA has been gathering data that can be used to help update meteoroid models:

- Radar observations of meteors have continued to be made outside the United States;
- Meteoroid "dust" was captured both in the stratosphere and in space and returned to Earth for analysis with the purpose of understanding dust from comets;
- Spacecraft surfaces that were examined for orbital debris impacts were also examined for meteoroid impacts; and
- The Max Plank Institute included a cosmic dust detector on the Cassini spacecraft to Saturn, as well as on the Galileo and Ulysses mission, providing data on the dust environment at very small sizes in the outer solar system to complement earlier measurements by Pioneer.[29]

Of additional importance, at least two spacecraft failures were believed to be associated with high meteor stream activity, even though current meteoroid models predicted no failures during any high meteor stream activity.[30] Past measurements of the meteoroid flux in all meteor showers had consistently measured an absence of meteoroids with decreasing size,[31] so that the predicted impact rate on satellites during meteor showers was many orders of magnitudes lower than required to be consistent with those two failures.

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[25] B.G. Cour-Palais, *Meteroid Environment Model-1969 (Near Earth to Lunar Surface),* NASA SP-8013, March 1969.

[26] D.J. Kessler, with assistance of ad hoc committee, *Meteoroid Environment Model-1970 (Interplanetary and Planetary),* NASA SP-8038, October 1970.

[27] "Space Station Program Natural Environment Definition for Design," SSP 30425 Revision B, 1994, available at http://paso.esa.int/3_Payload_Safety/SSP-30425%20RevB.pdf, accessed July 6, 2011.

[28] D.S.F. Portree and J.P. Loftus, *Orbital Debris: A Chronology,* NASA/TP-1999-208856, NASA, Washington, D.C., January 1999.

[29] E. Grün, "Earth Meteoroid Environment," presentation to the Committee for the Assessment of NASA's Orbital Debris Programs, March 10, 2011, National Research Council, Washington, D.C.

[30] W.J. Cooke, "Overview of NASA's Meteoroid Program," presentation to the Committee for the Assessment of NASA's Orbital Debris Programs, December 13, 2010, National Research Council, Washington, D.C.

[31] B.G. Cour-Palais, *Meteroid Environment Model—1969 (Near Earth to Lunar Surface),* NASA SP-8013, March 1969.

In an attempt to explain the failures, address the uncertainties in the existing meteoroid models, take advantage of data gathered over the past 40 years, and gather new data, NASA's Office of Safety and Mission Assurance and NASA Headquarters funded the establishment of the MEO at MSFC in 2004, with a budget of about $650,000 per year. MEO was created in part as a response to the Columbia Accident Investigation Board, which noted that NASA lacked means of monitoring meteoroid activity for post-event assessments and that a central office for meteoroid work was required within NASA to reverse loss of expertise and knowledge on the topic within the agency. The MEO is NASA's technical lead for defining the meteoroid environment using radar and optical measurements, performing data analysis, and developing models that can be used together with test results from the HITF at JSC.

In the past 6 years, the MEO has improved models describing meteor streams and storms and regularly provides forecasts. It monitors meteor activity using a radar located in Ontario, Canada, and a network of all-sky optical cameras. The optical camera images are available online, where a near-instant analysis is performed to determine the orbit of each meteor observed. Although much new information has been obtained—enough to identify necessary updates to existing models—much more can and should be done to safely achieve NASA's strategic goal to "extend and sustain human activities across the solar system."[32]

Finding: NASA's meteoroid and orbital debris programs have used their resources responsibly and have played an increasingly essential role in protecting the safety of both crewed and uncrewed space operations.

Finding: The increasing responsibilities given to NASA's meteoroid and orbital debris programs have put pressure on the programs' allotted resources. The increasing scope of work, and the complexity and severity of the debris and meteoroid environment, are outpacing in real dollars the decreasing funding levels of NASA's MMOD programs.

ADDITIONAL MMOD EFFORTS

The programs and activities described above represent NASA's primary efforts in MMOD research. During the course of its study, the committee became aware of smaller research projects occurring at individual centers (for instance, MMOD support for Project Orion at NASA Ames Research Center[33] or, also at NASA Ames, research to improve the accuracy of debris orbit prediction[34]). The committee did not have the time or resources to conduct a thorough review of these smaller efforts.

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[32] NASA, *2011 NASA Strategic Plan,* Washington, D.C., February 14, 2011, p. ii, available at http://www.americaspace.org/wp-content/uploads/2010/12/NASA_Strategic_Vision_2011.pdf, accessed July 6, 2011.

[33] J. Vander Kam, "NASA Ames Micro-Meteoroid and Orbital Debris (MMOD) Support for Project Orion," presentation to the Committee for the Assessment of NASA's Orbital Debris Programs, April 22, 2011, National Research Council, Washington, D.C.

[34] W. Marshall, "Debris Efforts at Ames," presentation to the National Research Council Committee for the Assessment of NASA's Orbital Debris Programs, April 22, 2011, National Research Council, Washington, D.C.

2

Orbital Debris Environment: Detection and Monitoring

Objects in the orbital debris environment are detected and monitored by a combination of remote and in situ measurements, and ground tests are used to help interpret those measurements. Calibration and analysis are required to interpret the measurements of the MMOD environment in terms of common parameters, usually impact flux (number per area per unit time) as a function of mass or diameter in various regions of space. Although parts of the NASA MMOD programs rely on measurements used to maintain the U.S. Strategic Command (USSTRATCOM) satellite catalog, NASA's primary program for measurement of debris uses sensors that sample only a portion of the debris environment, and the program performs a statistical analysis of the data to estimate the number of objects. That is, the sensors measure the number of objects per unit of time passing through a relatively small, but defined, volume of space. Orbital telemetry elements of objects in the catalog are converted to flux,[1] and this calculated flux can then be compared to the measured flux to test sensor calibration.

Orbital debris and meteoroids less than 10 cm in size in low Earth orbit (LEO) are measured with ground-based telescopes and radar and by examining the surfaces of returned spacecraft. Each type of sensor is capable of detecting debris of increasingly smaller sizes. Figure 2.1 compares the current measured orbital debris flux with the meteoroid flux for altitudes below 600 km. Both radar and optical measurements show an orbital debris flux increasing with altitude, up to 900 km, where the flux of 1-cm debris is measured by Haystack as being about 10 times larger than that indicated by optical measurements. At geosynchronous Earth orbit (GEO) altitudes, ground radar and telescopes are used to track the orbital debris environment, where the cataloged sizes are larger than 1 meter. Figure 2.2 illustrates the number of uncataloged objects detected near GEO by the Michigan Orbital Debris Survey Telescope (MODEST), a telescope located in Chile and configured to look for uncataloged objects.[2] Although the cataloged population in LEO contains all debris above 10 cm in size, in GEO the detection threshold for the satellite catalog is about 1 m.

The flux of orbital debris of the smallest sizes (less than about 1 mm) is obtained by analyzing the surfaces of satellites returned to Earth. The major uncertainty with these measurements lies in relating the damage measured on a particular returned surface to the damage measured on other types of surfaces or structures. This uncertainty is reduced through hypervelocity testing of various types of surfaces and structures. However, data of this type has been limited to impacts at altitudes below 600 km, the upper limit of space shuttle operations. For debris of larger

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[1] Kessler, D.J., Derivation of the collision probability between orbiting objects: The lifetimes of Jupiter's outer moons, *Icarus* 48:39-48, 1981.

[2] NASA Orbital Debris Program Office, *Orbital Debris Mitigation and Reentry Risk Management Course*, NASA Johnson Space Center, Houston, Tex., 2010.

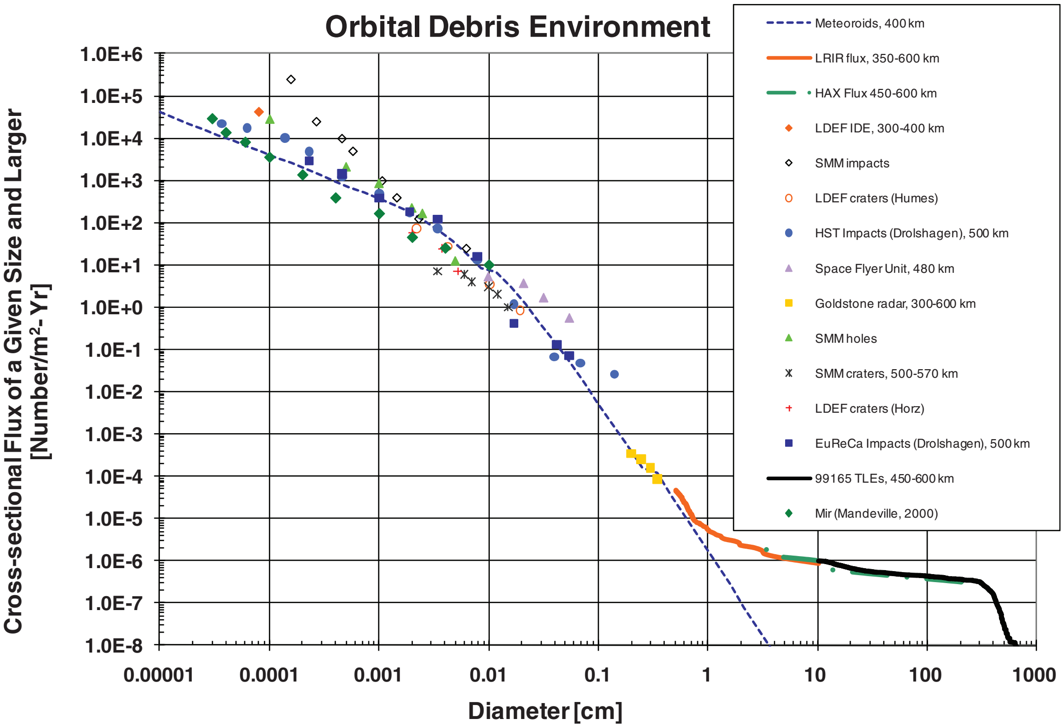

FIGURE 2.1 Measurements of orbital debris below 600 km are compared to the meteoroid flux at altitudes below 600 km. The orbital debris measurements (in some cases, averaged over several altitudes below 600 km) reflect use of the cataloged objects (99165 two-line elements), Haystack Auxiliary (HAX) radar, Haystack Long Range Imaging Radar, Goldstone radar, and returned spacecraft surfaces. At higher altitudes, the orbital debris flux increases with altitude, up to 900 km, where HAX has measured the flux of 1-cm objects as being about 10 times larger. The meteoroid flux remains nearly constant over this region. SOURCE: Courtesy of NASA-JSC, from Orbital Debris Program Office, "APPEL Orbital Debris Mitigation & Reentry Risk Management Course," CD, NASA Johnson Space Center, Houston, Tex., 2010, Part 1B, pp. 18 and 27.

sizes (between 2 mm and 10 cm in LEO), an exposed surface larger than that of a typical satellite is required to obtain a meaningful sample of "impacts," so ground telescopes and short-wavelength radars are used. However, neither telescopes nor radars actually track the objects that are detected; rather, they stay in a "staring mode" that essentially counts the number of objects passing through their relatively small field of view. While the debris is in the field of view, its direction of motion, signal strength, and range (for radar) or angular velocity (for telescopes) are measured. The largest source of uncertainty with these sensors exists in interpreting the signal strength in terms of the size or mass of the object passing through the field of view.

Signal strength is reported by telescopes in units of stellar magnitude, and by radar as radar cross section (RCS). Stellar magnitude is related to RCS statistically by using a sample of small fragments in which both RCS and magnitude are measured for each object.[3] An advantage of detecting uncataloged debris with both radars and telescopes is finding debris that may not be seen by one or the other alone. In 1995, NASA began operations of the NASA-built and NASA-designed 3-meter Liquid Mirror Telescope (LMT). However, as a result of budget cuts, the LMT was shut down in 2001. Although the LMT was providing useful data on uncataloged debris, the amount of debris found was less than predicted as a result of its lower than expected albedo. The decision to discontinue opera-

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[3] D.J. Kessler and K.S. Jarvis, Obtaining the properly weighted average albedo of orbital debris from optical and radar data, *Advances in Space Research* 34(5):1006-1012, 2004.

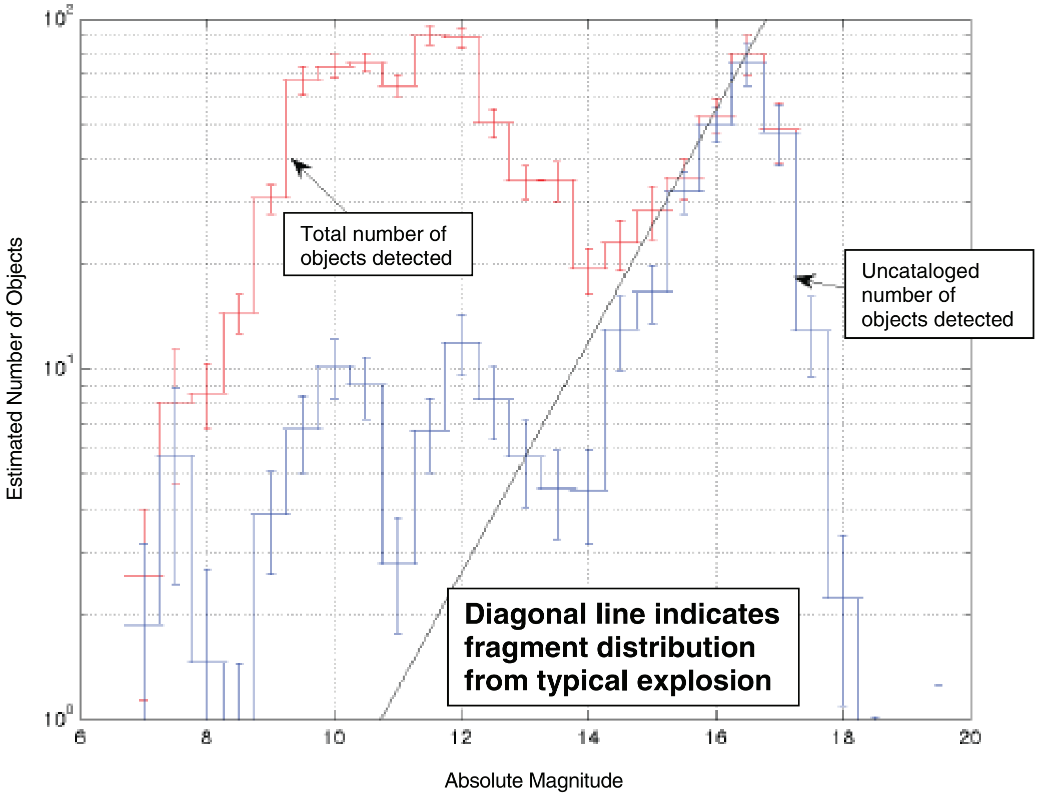

FIGURE 2.2 Uncataloged objects detected by MODEST compared to a total detected population near geosynchronous Earth orbit (GEO) altitude, indicating a significant population of objects in GEO that are uncataloged, possibly as a result of explosions near GEO. The diagonal line represents what the size of the population might be as the result of an explosion in GEO and suggests that such an event may be the source of this smaller debris; however, further analysis and observation will have to be performed to determine the source of these uncataloged objects and whether the size distribution will continue along this line for absolute magnitudes larger than 16. SOURCE: Adapted, courtesy of NASA-JSC, from Orbital Debris Program Office, "APPEL Orbital Debris Mitigation & Reentry Risk Management Course," CD, NASA Johnson Space Center, Houston, Tex., 2010, Part 1B, pp. 18 and 27.

tions of the LMT left only the remote observations using radar, which continue today and have become the most important technique for monitoring the debris environment for debris ranging in size between 2 mm and 10 cm.

NASA's orbital debris monitoring efforts currently receive data from three radars: Haystack (debris to 6 mm) and Haystack Auxiliary (HAX) (to 2 cm) in Westford, Massachusetts, and Goldstone (to 2 mm) in California's Mojave Desert. Following a significant debris-producing event, these radars are oriented to measure the flux of small debris produced in the stream of fragments generated by the event in order to test the debris source models. The most important limitation of these radars is their location; their higher latitude limits to orbital inclinations greater than about 28 degrees any observations of uncataloged debris; in addition, debris from objects in a Molniya-type orbit (which is highly elliptical, with an apogee near geosynchronous altitude and a perigee in the Southern Hemisphere) cannot be detected, because most of the U.S. ground-based sensor systems are in the Northern Hemisphere. Some of the limitations with respect to observational inclination will be resolved with remote operations by NASA of the Meter-Class Autonomous Telescope (MCAT) at Kwajalein Atoll in the Pacific Ocean beginning in 2012. This low-latitude location will permit detection of uncataloged debris at low inclinations, although not to sizes as small as can be detected by current radar capabilities. MCAT will also detect GEO debris as small as 10 cm.

The major uncertainty in these measurements is in relating RCS to the physical characteristics of the debris.

Ground tests combined with radar calibrations have been used to address this issue. Between 1991 and 1992, DOD conducted a series of hypervelocity tests to simulate the hypervelocity breakup of a payload, known as the Satellite Orbital Debris Characterization Impact Test (SOCIT) series. In the fourth and final test, a flight-ready, 35-kg transit payload was hit with a 150-g projectile at 6 km/s.[4] The results of that test not only helped shape future debris breakup models for the LEGEND (LEO-to-GEO Environment Debris) model, but also supplied a number of fragments that could be used to measure RCS on a radar range, under the assumption that the fragments had physical characteristics similar to those of fragments in orbit. The results were a distribution of possible RCS returns from objects having a particular size, mass, and shape. From these distributions, an orbital debris size estimation algorithm (also known as the Size Estimation Model, or SEM) was developed to relate RCS to size.[5]

Limitations of the SEM became obvious when the Haystack radar begin to discover new sources of debris. The most-verified new source of debris was droplets of sodium potassium (NaK) from Russian radar ocean reconnaissance satellites. Using the SEM, it was concluded that 60 kg of NaK were in orbit.[6] Since these droplets are simply liquid-metal spheres, they each have a well-understood RCS that depends only on their size. When an algorithm was applied to the measured RCS distribution of NaK objects, their total mass was calculated at 150 kg.[7] The reason for the difference in total mass is that the RCS is larger for objects with certain orientations than for any metal sphere of the same size. Consequently, the SEM includes biases toward smaller objects when a large number of smaller-size objects are known to exist.

The Haystack radar also discovered objects with orbital characteristics expected for aluminum oxide slag from solid-rocket-motor exhaust[8]—particles that would likely be nearly spherical but non-metallic. Little data exists on the amount of slag that solid-rocket motors are likely to produce or on their expected RCS. Other sources of debris, such as fragments from upper-stage rockets and satellites made of a larger range of materials, were not included in the sample of objects used to establish the SEM. Obtaining samples of these fragments requires a ground test program similar to the 1991 to 1992 series of SOCIT tests, and such a test program does not currently exist.

The SEM is important to both the Orbital Debris Environment Model (ORDEM), which must correctly convert RCS to size of debris and hazard, and to the LEGEND model, which must properly capture the relative contributions of various sources of debris to help NASA "lead the continued development and adoption of international and industry standards and policies to minimize debris, such as the United Nations Space Debris Mitigation Guidelines" (p. 7) as required in the 2010 National Space Policy.

Finding: The current lack of radar cross-section calibrations for fragments from a larger range of materials used in modern satellites and rocket bodies, as well as non-fragmentation debris, represents a significant source of uncertainty in interpreting key measurements of the orbital debris environment.

Figure 2.3 summarizes the capabilities of the sensors on which the NASA orbital debris programs depend to define the orbital debris environment and summarizes the types of damage that debris of different sizes can cause. Missing from the orbital debris monitoring program is a capability to monitor the flux of debris smaller than 2 mm in size as a function of both time and altitude. Lessons can be learned by reflecting on the early research done during the 1960s to understand the meteoroid hazard.

Like the flux for orbital debris, the flux for meteoroids larger than a few millimeters has been determined using

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[4] D.M. Hogg, T.M Cunningham, and W.M. Isbell, *Final Report on the SOCIT Series of Hypervelocity Impact Tests,* Report No. WL-TR-93-7025, Wright Laboratory, Armament Directorate, Wright-Patterson Air Force Base, Ohio, July 1993.

[5] E.G. Stansbery, C.C. Pitts, G. Bohannon, et al., *Size and Orbit Analysis of Orbital Debris Data Collected Using the Haystack Radar,* NASA JSC-25245, NASA Johnson Space Center, Houston, Tex., 1991.

[6] D.J. Kessler, M.J. Matney, R.C. Reynolds, R.P. Bernhard, E.G. Stansbery, N.L. Johnson, A.E. Potter, and P.D. Anz-Meador, "A Search for a Previously Unknown Source of Orbital Debris: The Possibility of a Coolant Leak in Radar Ocean Reconnaissance Satellites," IAA-97-IAA.6.3.03, presented at the 48th International Astronautical Conference, Turin, Italy, October 6-10, 1997 (also pp. 129-150 in *Space Safety and Rescue 1997* (G.W. Heath, ed.)*,* Science and Technology Series, Volume 96, American Astronautical Society, Springfield, Va.).

[7] P. Krisko, NASA's sodium potassium generation and propagation model, *Orbital Debris Quarterly News* 8(1):6-7, 2004, available at http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv8i1.pdf, accessed July 7, 2011.

[8] D.J. Kessler, N. Johnson, E. Stansbery, R. Reynolds, K. Siebold, M. Matney, and A. Jackson, The importance of non-fragmentation sources of debris to the environment, *Advances in Space Research* 23(1):149-159, 1999.

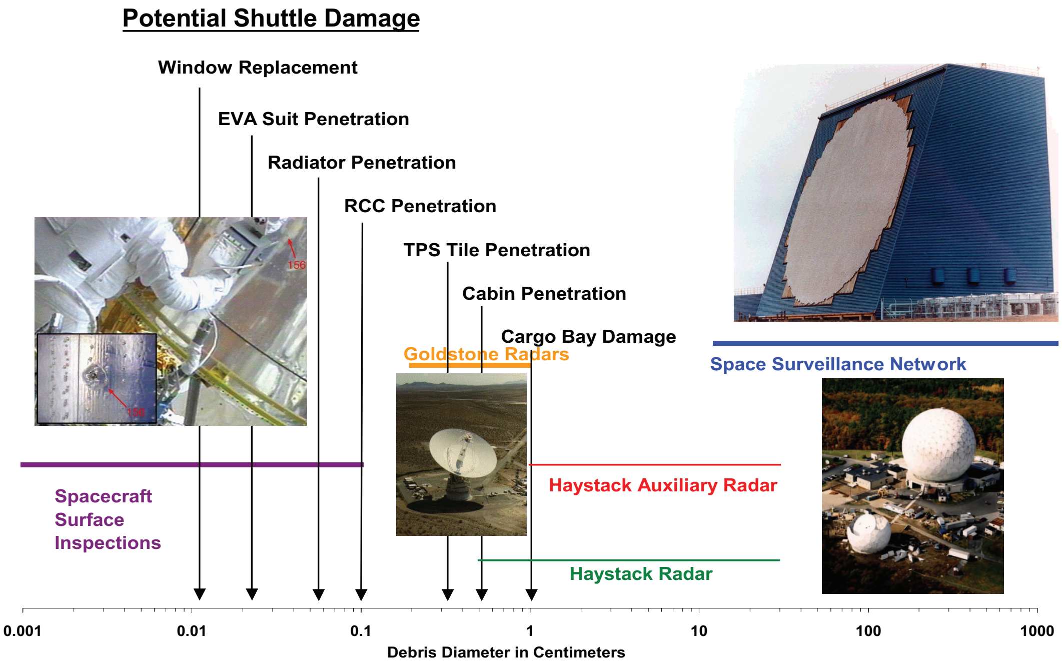

FIGURE 2.3 Orbital debris program sensor capabilities for low Earth orbit orbital debris measurements. The capabilities for characterization of small debris are a function of returned samples and a variety of remote measurement capabilities. The importance of these size ranges is highlighted by their associated potential effects on space shuttle subsystem reliability. SOURCE: Adapted, courtesy of NASA, from Lyver, J., "NASA Micrometeoroid and Orbital Debris Program Overview to National Research Council," presentation to the Committee for the Assessment of NASA's Orbital Debris Programs, December 13, 2010, National Research Council, Washington, D.C., p. 10.

remote observations, in the case of meteoroids by measuring the meteor ion trail in Earth's atmosphere. Smaller-size meteoroids have been measured using a multitude of in situ sensors on satellites. Similar to the situation with measurements of orbital debris, there has been more uncertainty in the remote sensing data for meteoroids than in the in situ data. The in situ data from satellites such as the three Pegasus satellites launched in 1965 has turned out to be critical in helping to resolve uncertainties in the remotely sensed data and was a major component in defining the parameters in meteoroid environment models used today. Given uncertainty in the current RCS calibrations, in situ data are also likely to be a major component in defining parameters in models of the orbital debris environment.

Although no major changes from 1960s in situ measurements of the background meteoroid flux have been detected, that is not the expectation for the orbital debris environment, which is predicted to be, and has been measured to be, much more dynamic than the meteoroid environment. Ironically, dynamic changes in the orbital debris environment were measured as a result of an experiment on the Long Duration Exposure Facility, which was intended to detect meteoroid streams. Instead of meteoroid steams, most of the 15,000 impacts detected were interpreted as being the result of Earth-orbiting debris streams.[9] The source of those debris streams is still uncertain, although some streams have been associated with solid rocket motors. In addition to helping to confirm RCS calibrations, the much higher flux measured with in situ instrumentation will translate to more quickly monitoring

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[9] J.P. Oliver, S.F. Singer, J.L. Weinberg, C.G. Simon, W.J. Cooke, P.C. Kassel, W.H. Kinard, J.D. Mulholland, and J.J. Wortman, LDEF Interplanetary Dust Experiment (IDE) results, pp. 353-360 in *LDEF—69 Months in Space*, Proceedings of the Third Post-Retrieval Symposium, November 8-12, NASA Langley Research Center, Hampton, Va., 1993; W.J. Cooke, J.P. Oliver, and C.G. Simon, The orbital characteristics of debris particle rings as derived from the IDE observations of multiple orbit intersections with LDEF, pp. 361-371 in *LDEF—69 Months in Space*, Proceedings of the Third Post-Retrieval Symposium, November 8-12, NASA Langley Research Center, Hampton, Va., 1993.

changes in the environment, and possibly to identifying the sources of those changes. Such in situ sensors are also likely to contribute to understanding spacecraft anomalies, as discussed in Chapter 10, "Spacecraft Anomalies."

Given the potential for rapid growth in the debris population, it is necessary to have a robust measurement program in place for detecting changes in the orbital debris environment quickly, and to increase the number of mitigation and remediation options available for use. If such a measurement program had been in place at the beginning of the space program, the consequences of explosions in orbit would likely have been detected, and mitigation guidelines put in place, much earlier. Similarly, early detection of the consequences of collisions in orbit might prompt a quicker recognition of the need for remediation actions.

Finding: NASA's orbital debris programs do not include the capability to monitor with in situ instrumentation the penetrating flux of objects smaller than a few millimeters. Data collected by in situ monitoring could be used to resolve uncertainties in measurements made remotely, to help identify new sources of debris, and to provide clues to the causes of spacecraft anomalies.

3

Orbital Debris Modeling and Simulation

As indicated in Chapter 1, “Introduction and Historical Background,” NASA’s meteoroid and orbital debris (MMOD) models create the foundation for the technical services provided by the Orbital Debris Program Office (ODPO), Meteoroid Environment Office (MEO), Hypervelocity Impact Technology Facility (HITF), and other NASA offices, in addition to being tangible artifacts used by the aerospace community to support analyses regarding space system performance related to debris and meteoroids. Figure 3.1 shows that relationships among the various models used.

Meteoroid modeling and simulation, including the Meteoroid Environment Model (MEM), are discussed separately in Chapter 4, “The Meteoroid Environment and its Effects on Spacecraft.” In addition, the committee notes that the collision avoidance operations are not discussed since they represent an operational capacity that is not directly supported by the NASA MMOD offices. Although there is significant related dialogue between NASA centers and personnel, collision avoidance operations are based solely on specific mission needs, as opposed to the foundational research and development that are the focus of the ODPO, the MEO, and the HITF.

GEOPROP and PROP3D (Table 3.1) are general-purpose orbital propagator models, and Solar Flux is a model for the solar flux component (i.e., 10.7-cm wavelength) that affects atmospheric density calculations. Figure 3.1 and Table 3.1 highlight the wide suite of MMOD models that NASA has developed (and continues to develop) in support of national policy development, mission operations, and international technical discussions.

The following models, which (with one exception) are used only by NASA, provide valuable insights and reflect the results of decades of testing, measurements, studies, and analysis.

- *SBM* produces distributions of fragments from a variety of breakup events for use by other models such as LEGEND and SBRAM. The model leverages empirical data from laboratory and on-orbit testing to provide an accurate depiction of explosions and collisions in space.[1]

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[1] For further information on SBM see D. McKnight, Determination of breakup initial conditions, *Journal of Spacecraft and Rockets* 28(4):470-477, 1991; D. McKnight, Determining the effects of space debris impacts on spacecraft structures, *Acta Astronautica* 26(7):501-512, 1992; D. McKnight, “Key Aspects of Satellite Breakup Modeling,” ESA SP-1, First European Conference on Space Debris, Darmstadt, Germany, April 5-7, 1993; D. McKnight, L. Nagl, and R. Maher, “Refined Algorithms for Structural Breakup Due to Hypervelocity Impact,” Hypervelocity Impact Symposium, Paper 82, Santa Fe, N.M., October 1994 (also *International Journal of Impact Engineering Proceedings* 17:547-558, 1994); D. McKnight, L. Nagl, C. Dobosz, and R. Maher, “Explosion Modeling and Simulation,” DNA-TR-94-11, August 1994; D. McKnight, L. Nagl, and R. Maher, “Fragmentation Algorithms for Strategic and Theater Targets (FASTT) Empirical Breakup Model,” DNA-TR-94-104, December 1994; D. McKnight, M. Fudge, and T. Maclay, *Satellite Orbital Debris Characterization Impact Test (SOCIT) Series Data Collection Report,* prepared under NASA contract NAS 9-19215, April 1995; D. McKnight, N. Johnson, M. Fudge, and T. Maclay, *Analysis of SOCIT Debris Data and Correlation to NASA’s Breakup Models,* prepared under NASA contract NAS 9-19215, July 1995.

TABLE 3.1 Summary of NASA MMOD Models and Their Interdependencies

Model	Function/Usage	Development	Latest Version	Models Used	Used By
ORDEM (Orbital Debris Engineering Model)	User-friendly, semi-empirical environment characterization, for current and short-term future (~30 years), of debris impact flux down to 10 µm in Earth orbit (LEO and GEO) based on returned samples, remote observations, modeling, historical changes, and trends. Available to the public.	Since 1970s, NASA has evolved through several codes; ORDEM96 was released in 1996.	ORDEM2000; ORDEM3.0 due out in late 2011/early 2012	SBM Solar Flux GEOPROP PROP3D	DAS/ BUMPER
MEM (Meteoroid Environment Model)	Semi-empirical meteoroid velocity and direction distribution for near-Earth and interplanetary (Mercury to asteroid belt) natural particulates down to 1 µg to predict flux on spacecraft surfaces. Available to the public.	Based on 2000-2004 work at University of Western Ontario.	Version 2.0 Lunar MEM2/ MEM CXP in 2008	Grün IFM	BUMPER
DAS (Debris Assessment Software)	Suite of tools (ORDEM, orbit propagators, and ballistic limit equations [BLE]) to assist NASA offices in verifying compliance with NASA STD 8719.14. Used widely inside and outside NASA. Available to the public.	NASA developed to accompany NASA standard practices starting in 1995.	DAS 2.0.1 2008	ORDEM "BLEs"/SBM	None
BUMPER	Semi-empirical model to determine the potential for debris and meteoroids to strike and penetrate spacecraft surfaces. Not available for public use.	NASA developed and started to apply in mid-1990s.	BUMPER II 2005	ORDEM/MEM	None
ORSAT (Object Reentry Survival Analysis Tool)	Simulates reentry of hardware to determine debris casualty area to calculate the reentry risk to people on Earth. Not available for public use.	NASA evolved since 1993 but also used to analyze many non-NASA objects.	ORSAT 6.0 2006	None	None
LEGEND (LEO-to-GEO Environment Debris)	Statistical, three-dimensional, debris evolutionary model for the study of the long-term debris environment for LEO, HEO, and GEO. Provides debris characteristics as functions of time, altitude, longitude, and latitude. Not available for public use.	NASA EVOLVE leveraged to create LEGEND in 2003.	2005, but undergoing continual upgrades	SBM GEOPROP PROP3D Solar Flux Launch Traffic	None
SBM (Standard Breakup Model)[a]	Semi-empirical model that determines the number, mass, velocity, and ballistic coefficient distributions of fragments produced down to 1 mm from a breakup event—collision and explosion. Not available for public use.	NASA has been developing SBM since 1970s; used by IADC since 2008.	2001	None	ORDEM DAS LEGEND SBRAM

TABLE 3.1 (continued)

Model	Function/Usage	Development	Latest Version	Models Used	Used By
SBRAM (Satellite Breakup Assessment Model)	Used to determine the short-term hazard (hours to days) from a single breakup event and separate from "background risk." Provides probability of collision over time for a given asset from a simulated breakup cloud. Not available for public use.	NASA developed its own version in 2006 and one for the Missile Defense Agency in 2007.	2006	SBM GEOPROP PROP3D	None

NOTE: The latest version is given if appropriate and/or known.

[a] The SBM is not a standalone software application available from NASA, although it is embedded in ORDEM, DAS, LEGEND, and SBRAM. In addition, all of the equations used in the SBM are available in N.L. Johnson, P.H. Krisko, J.-C. Liou, and P.D. Anz-Meador, NASA's new breakup model of Evolve 4.0, *Advances in Space Research* 28(9)1377-1384, 2001.

- *LEGEND* depicts the long-term evolution of the debris flux as a function of latitude, longitude, altitude, size, and time. Considering longitude permits analysis of constellations or any orbits that may include a stable argument of perigee or right ascension of ascending node. LEGEND contains a number of submodels: the traffic model describes the frequency of launches, the initial orbits of objects placed into orbit, and the physical characteristics of each object placed into orbit; the atmospheric decay model includes the Jacchia atmospheric density model plus a solar activity model; and various debris source models describe sources, such as SBM, exhaust from solid rocket motors, and coolant leaks. Values for the probability of explosion are assigned to certain objects, and probabilities of collision are calculated for all objects. Probabilities are combined with a random number genera-

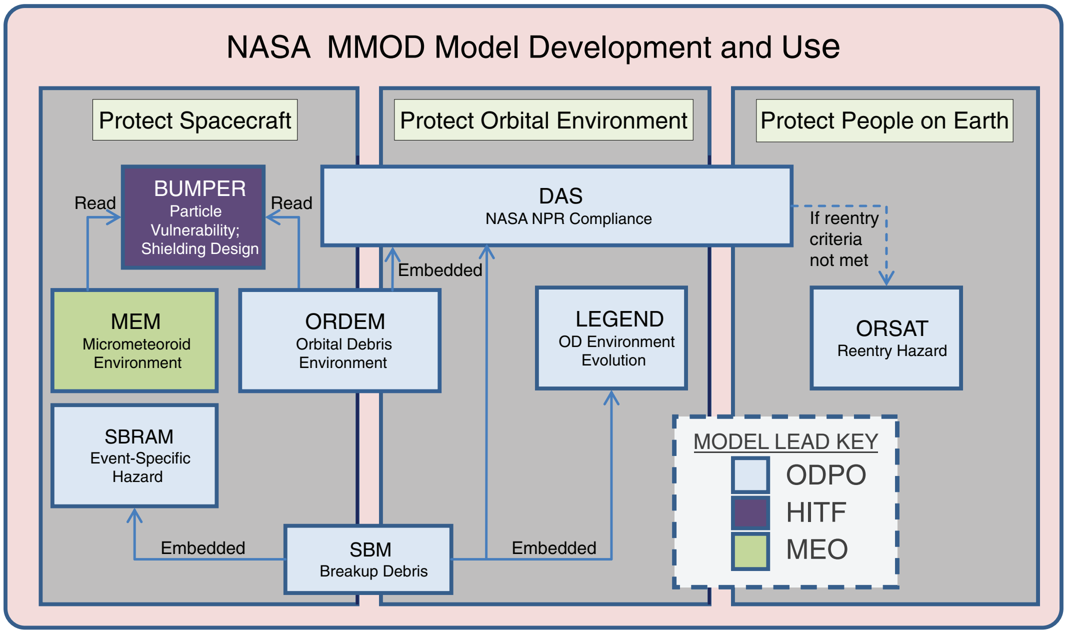

FIGURE 3.1 NASA MMOD model development and use. The models developed, used, and delivered by NASA cover a wide spectrum of applications and needs for both NASA and non-NASA space operators. When a model is "embedded" in another, it is subsumed by that top-level model and does not run independently of it. When a model is "read" by another, the top-level model is using the output of the first model as an input to its analysis.

tor to predict if an explosion or collision will occur. Consequently, every run of the program results in a different sequence of events. Typically after 100 runs the resulting fluxes are averaged. Predicted averages are compared with observational data to determine if updates to the model are required; after adjustments in the model, the results become part of a historical database that sets the initial conditions for any future projections.[2]

- *ORSAT* provides a high-fidelity determination of the risk to people on the ground from reentering space systems. ORSAT is discussed more fully in Chapter 8.
- *BUMPER* determines spacecraft vulnerability from particulates and facilitates shield-design processes for spacecraft based on input from the MEM and ORDEM particulate environment models. BUMPER is discussed more fully in Chapter 6. NASA used the BUMPER code to calculate the probability of MMOD critical impact damage for space shuttle missions, and uses it to calculate the risk of MMOD penetration for the International Space Station (ISS), extravehicular activity (EVA) suits, and other spacecraft. The major limitations of BUMPER are that (1) it calculates only a portion of the MMOD risk to a spacecraft (the probability of a penetration, however that is defined for the particular spacecraft under consideration) and is not able to calculate the total MMOD risk (which would include the probability of spacecraft loss or kill), (2) it provides only a point estimate of MMOD risk with no assessment of the associated uncertainty, and (3) it does not take into consideration the possibility of non-spherical particle impacts in its risk-calculating modules and algorithms.[3]
- *SBRAM* provides calculations of short-term hazards to other spacecraft from fragmentation events on orbit. A basic combination of the SBM and general purpose propagators, SBRAM permits rapid examination of the effect that a breakup event may have on space assets hours to days after an event. As such, it is uniquely tailored to permit the creation of specific scenarios and has been developed for use by NASA and for other government partners.

Because they model complex physical phenomena and require operation by skilled users, LEGEND, ORSAT, and BUMPER are not made available to the public. Although the NASA SBM model has not been updated since 2001,[4] it is used by the LEGEND, SBRAM, and DAS programs. As such, any deficiencies in the model will affect a variety of studies, analysis, and support to customers. In addition, the data from the major on-orbit collisional breakup events in 2007 (the Chinese ASAT event; see Box 1.2 in Chapter 1) and 2009 (the Iridium–Cosmos collision; see Box 9.1 in Chapter 9) have not been considered in the current model.[5]

NASA is planning to update the SBM with full-scale tests involving “new-construction” satellites—satellites constructed using processes and materials designed to prevent or at least minimize the creation of addition orbital debris. However, it is not at all clear that the new-construction satellites will be generating significant orbital

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[2] For further information on LEGEND see J.-C. Liou, D.T. Hall, P.H. Krisko, and J.N. Opiela, LEGEND—A three dimensional Leo-to-Geo debris evolutionary model, *Advances in Space Research* 34:981-986, 2004; D.J. Kessler, M.J. Matney, R.C. Reynolds, R.P. Bernhard, E.G. Stansbery, N.L. Johnson, A.E. Potter, and P.D. Anz-Meador, *The Search for a Previously Unknown Source of Orbital Debris: The Possibility of a Coolant Leak in Radar Ocean Reconnaissance Satellites,* JSC-27737 and LMSMSS32426, NASA Johnson Space Center, Houston, Tex., February 21, 1997; E.L. Christiansen, *Handbook for Designing MMOD Protection,* NASA TM-2009-214785, NASA Johnson Space Center, Houston, Tex., 2009; W.H. Jolly and J. Williamsen, “Ballistic Limit Curve Regression for Freedom Station Orbital Debris Shields,” AIAA Paper No. 92-1463, AIAA Space Programs and Technologies Conference, Huntsville, Ala., American Institute of Aeronautics and Astronautics, Reston, Va., 1992; W.P. Schonberg, H.J. Evans, J.E. Williamsen, R.L. Boyer, and G.S. Nakayama, Uncertainty considerations for ballistic limit equations for aerospace structural systems, Paper No. IMECE2005-79709, *Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition,* Orlando, Fla., November 5-11, 2005, American Society of Mechanical Engineers, New York, N.Y., 2005; J.E. Williamsen, W.P. Schonberg, and A.B. Jenkin, On the effect of considering more realistic particle shape and mass parameters in MMOD risk assessments, *Advances in Space Research* 47:1006-1019, 2011; D. Kessler, N. Johnson, E. Stansbery, R. Reynolds, K. Siebold , M. Matney and A. Jackson, The importance of non-fragmentation sources of debris to the environment, *Advances in Space Research* 23(1):149-159, 1999.

[3] National Research Council, *Protecting the Space Shuttle from Meteoroids and Orbital Debris*, National Academy Press, Washington, D.C., 1997, available at http://www.nap.edu/catalog.php?record_id=5958, accessed July 7, 2011.

[4] N.L. Johnson, P.H. Krisko, J.-C. Liou, and P.D. Anz-Meador, NASA’s new breakup model of Evolve 4.0, *Advances in Space Research* 28(9):1377-1384, 2001.

[5] See J.-C. Liou and N.L. Johnson, Physical properties of the large Fengyun-1C breakup fragments, *Orbital Debris Quarterly News* 12(2):4-5, 2008; M. Matney, Small debris observations from the Iridium33/Cosmos 2251 collision, *Orbital Debris Quarterly News* 14(2):6-8, 2010, available at http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv14i2.pdf; J. Oberg, “U.S. Satellite Shootdown: The Inside Story,” *IEEE Spectrum*, August 2008, available at http://spectrum.ieee.org/aerospace/satellites/us-satellite-shootdown-the-inside-story.

debris in the future. Since there are far more "old-construction" satellites in orbit, it would appear that the old-construction satellites would contribute more debris to the environment. It would be instructive to know what will be the relative mass of old-construction to new-construction satellites in orbit over time; that information would help NASA determine how test targets should be constructed and with which materials. In addition, the shape of a debris fragment is known to have an influence on the penetrability of impacts from debris and on the damage levels sustained by spacecraft,[6,7] and the fragmentation physics varies significantly between (1) thin-walled, hollow cylinders like rocket bodies and human habitation modules and (2) compact, robotic satellites, a consideration that should also be factored into the development of a new SBM.

Finding: Correctly characterizing the shape and material properties of orbital debris is critical to correlating the results of ground-based satellite impact tests with radar cross-section data and thus to predicting the damage caused by debris particles, yet there has been little effort to include realistic effects of shape in the standard breakup model. These enhancements would also serve to improve BUMPER's accuracy in predicting risks.

Recommendation: The NASA Orbital Debris Program Office should expand its efforts to more accurately incorporate data on sources of debris into the standard breakup model, especially (1) empirical results from recent major on-orbit collisions, (2) data from laboratory rocket body collision tests (which need to be planned and conducted), (3) results from hypervelocity impact tests with payloads using newer construction methods and materials, and (4) enhanced data on fragment shape characteristics.

The following two models developed by NASA are provided to the public:[8]

- *DAS,* a suite of tools originally provided to assist NASA offices in verifying compliance with NASA procedural requirements for NASA STD 8719.14, has been used by many non-NASA missions to ascertain their systems' debris-related performance.[9] DAS contains ORDEM, SBM, ballistic limit equations (BLEs) predicting the penetrability of debris, and a simplified reentry demise model integrated within a user-friendly graphical user interface that provides threshold evaluations of adherence to the NASA standard for limiting debris. DAS puts significant analytic capability in the hands of the operator, but it does not provide the flexibility to analyze these issues quantitatively. For example, to examine reentry disintegration of hardware more precisely, one would apply ORSAT. Similarly, to determine a shield design (versus a simple ability to survive the particulate environment), one would apply BUMPER.
- *ORDEM* is the empirical space debris environment model that estimates as a function of size and altitude the number of debris objects that are likely to impact a spacecraft. This engineering model is based almost entirely on measurements, with some interpolations and extrapolations required when no measurements are available (e.g., for debris smaller than 1 mm at altitudes above 600 km where no measurements have been taken). Since the measurements of the debris environment include measurements of flux, the uncertainties associated with the ORDEM engineering model are limited almost entirely to uncertainties in translating any measured "size" into some level of damage.

Although NASA has made several important improvements in ORDEM since its latest formal release in 2000, a new version of that model that incorporates those changes has not been released. Given that the environment is

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[6] L. Anselmo, A. Cordelli, P. Farinella, C. Pardini, and A. Rossi, Modelling the evolution of the space debris population: Recent research work in Pisa, pp. 339-344 in *Proceedings of the Second European Conference on Space Debris, Darmstadt, Germany, March 17-19, 1997,* ESA SP-393, European Space Operations Centre, European Space Agency, Paris, France, 1997, available at http://articles.adsabs.harvard.edu//full/1997ESASP.393..339A/0000339.000.html, accessed July 8, 2011.

[7] J. Opiela and N. Johnson, "Improvements to NASA's Debris Assessment Software," 2007.

[8] The Meteoroid Environment Model (MEM), which is also provided free to the public, is discussed in Chapter 4.

[9] J. Opiela and N. Johnson, "Improvements to NASA's Debris Assessment Software," 58th International Astronautical Congress, IAA-01-IAA.6.6076, Hyderabad, India, International Academy of Astronautics, Paris, France, September 2007, available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070013703_2007011171.pdf, accessed July 8, 2011.

constantly changing, updates should be made consistent with major changes in the environment and with enhanced understanding of environmental features. Debris-shape characterization is ongoing within NASA, and some rudimentary information is to be included in the forthcoming ORDEM update. This information is important because there is significant shape variation among larger particles, where criticality for human-rated spacecraft is defined relative to mission failure or crew loss, and not just in terms of whether there is impact damage.

The update to ORDEM2000, known as ORDEM 3.0 (formerly referred to as ORDEM 2010), is slated to include a definition of the environment past LEO, an explicit characterization of orbital debris flux uncertainties, and the introduction of material densities into the model.

Recommendation: NASA's Orbital Debris Program Office should release the next version of the Orbital Debris Environment Model as soon as possible and provide updates on a regular basis or as often as required as a result of major changes to the orbital debris environment or improved characterization of that environment, including characterization of debris shape, as applicable.

4

The Meteoroid Environment and Its Effects on Spacecraft

BACKGROUND

Meteoroids are small, solid particles, formally defined by the International Astronomical Union as being considerably larger than an atom or molecule and smaller than an asteroid.[1] Meteoroids are generated mainly from collisions between asteroids and the decay of comets, although a small percentage may originate from stellar activity outside the solar system. The precise size limits applying to the term "meteoroid" have been debated extensively in the literature,[2] but for the purposes of this report an operational definition covers the size range from 1 micron to 10 cm in diameter. The lower bound represents solid particles, which, once created through collisions, are often expected to be on unbound orbits due to radiation pressure from the Sun; the upper (arbitrary) limit represents meteoroids, which are so infrequent as to be negligible as primary impactors on spacecraft. This is also the size at which the meteoroid flux is two orders of magnitude lower than the space debris flux in portions of low Earth orbit (LEO). Flux refers to the number of meteoroids of a certain mass or larger crossing a fixed surface in space per unit time.[3]

In contrast to the space debris environment, the meteoroid environment in near-Earth space is not affected by launch activity and subsequent operational practices. Beyond LEO, the flux of meteoroids up to the 5- to 10-cm-size range is the long-term averaged dominant impactor population for spacecraft, whereas in LEO meteoroids and orbital debris between 10 microns and 1 mm are comparable in flux. For sizes larger than 1 mm in LEO, orbital debris is the dominant impactor population.

The meteoroid population can be divided into two broad components: sporadic meteoroids and stream meteoroids. Stream meteoroids have a common, recent (less than 100,000 years) origin and thus all follow nearly identical heliocentric orbits. When this stream intersects Earth, each particle (or meteoroid) colliding with Earth's atmosphere produces heat, light, and ionization. These phenomena associated with a meteoroid impacting a planetary atmosphere are collectively termed a meteor (i.e., a plasma). As meteors travel along parallel paths in the

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[1] P.M. Millman, Meteor news: A report on meteor terminology, *Journal of the Royal Astronomical Society of Canada* 55:265-267, 1961, available at http://adsabs.harvard.edu/full/1961JRASC..55..265M, accessed July 13, 2011.

[2] See also M. Beech and D. Steel, On the definition of the term 'meteoroid,' *Quarterly Journal of the Royal Astronomical Society* 36:281-284, 1995, available at http://articles.adsabs.harvard.edu//full/ 1995QJRAS..36..281B/0000281.000.html; A.E. Rubin and J.N. Grossman, Meteorite and meteoroid: New comprehensive definitions, *Meteoritics and Planetary Science* 122:114-122, 2010, available at http://cosmochemists.igpp.ucla.edu/definitions.pdf.

[3] H. Klinkrad, *Space Debris: Models and Risk Analysis*, Springer Praxis, Chichester, U.K., 2006.

TABLE 4.1 Major Nighttime Meteor Showers Visible from Earth

Shower	Max Date	ZHR	Θ ($\times 10^{-6}$)	RA	DEC	Speed (km/s)	Parent
Quadrantids	Jan. 3	120	8.4	15 20	49	43	2003 EH1
Lyrids	Apr. 22	20	4.6	18 10	34	48	C/1861 G1 (Thatcher)
η-Aquariids	May 6	60	6.4	22 30	–2	66	1P/Halley
S. δ-Aquariids	Jul. 29	20	6.2	22 44	–16	43	
Perseids	Aug. 13	90	6.0	3 08	58	60	109P/Swift-Tuttle
Draconids	Oct. 8	var	var	17 28	54	23	9P/Giacobini-Zinner
Orionids	Oct. 21	20	2.2	6 20	16	67	1P/Halley
S. Taurids	Nov. 5	10	1.0	3 34	14	31	2P/Encke
N. Taurids	Nov. 12	15	1.4	4 00	22	30	2P/Encke
Leonids	Nov. 17	15	1.9	10 12	22	71	55P/Tempel-Tuttle
Geminids	Dec. 14	100	2.3	7 28	33	36	3200 Phaethon
Ursids	Dec. 22	10	2.2	14 36	75	35	8P/Tuttle

NOTE: ZHR, zenithal hourly rate, the approximate number of shower-related meteors an observer would see under ideal conditions; Max Date, the date at which the highest flux of meteors is normally expected each year; Θ ($\times 10^{-6}$), the flux of meteors brighter than astronomical absolute magnitude +6.5 per $km^{-2}s^{-1}$ at the time of the maximum; RA, the right ascension of the radiant in equatorial coordinates at the time of the shower maximum; DEC, the declination of the radiant in equatorial coordinates at the time of the shower maximum; Speed (km/s), the speed of a meteor at the top of the atmosphere; Parent, the parent body (comet or asteroid) from which the meteoroid stream is believed to originate.
SOURCE: Adapted, courtesy of the Royal Astronomical Society of Canada, from the *Observers Handbook* (2011).

atmosphere (having identical orbits about the Sun), they appear to emanate from a particular point in the sky (termed a "shower radiant"); the meteor shower's name is derived from the constellation where this radiant is found. The comet or asteroid "parent" for many streams is known. Table 4.1 lists a selection of the strongest nighttime meteor showers visible at Earth, along with their parent bodies. Because meteor showers consist of many meteoroids traveling on similar orbits in a stream, which intersect Earth at a fixed point in its orbit during a short interval of time (typically on the order of days), the showers occur at about the same time each year. Several showers show strong variations in activity related to the details of how dust is produced and subsequently evolves in the stream. Such showers can produce strong flux enhancements for short periods in certain years. Examples include the Leonids in 1999 and the October Draconids in 1933 and 1946. Box 4.1 discusses meteor storms and spacecraft safety.

Meteoroids not found in streams are termed "sporadic meteors." While they do not have a clear common origin, the sporadic background meteoroid population as detected at Earth shows strong directionality, reflecting the general orbital properties of the meteors' parent body population. At Earth, in particular, several major sporadic meteor sources are noticeable with radiant diameters on the order of 20 degrees, as shown in Figure 4.1.[4] Meteor showers from stream meteoroids are well known, whereas the sporadic meteoroid population is less well understood.

Unlike knowledge of orbital debris, knowledge of meteoroids results in part from ground-based observations of the interaction of meteoroids with the atmosphere (used as a detector for this purpose) to form a meteor (the plasma) at an altitude of between approximately 70 and 140 km. Broadly speaking, ground-based optical and radar instruments can detect both the plasma formed around a meteoroid particle traveling at its velocity—called the "head" or "radar head echo"—and the quasi-stationary plasma that can extend for kilometers behind the meteoroid, called the "trail" or "wake." Direct measurement of the meteoroid is not possible using ground-based observational techniques, and significant modeling effort is required to translate measured meteor parameters to meteoroid

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[4] J. Jones and P. Brown, Sporadic meteor radiant distributions—Orbital survey results, *Royal Astronomical Society, Monthly Notices* 265:524-532, 1993, available at http://articles.adsabs.harvard.edu//full/1993MNRAS.265..524J/0000524.000.html, accessed July 13, 2011.

BOX 4.1
Meteor Storms and Spacecraft Safety

The NASA meteoroid program established during the 1960s provided estimates of the background meteoroid impact environment, which was not found to be a show-stopping hazard to the Apollo program and subsequent crewed missions in low Earth orbit. That effort determined that the dominant impact threat from meteoroids was from the random background of particles, rather than the visually spectacular but less numerous (at the small dust sizes of concern to spacecraft) meteor showers.

However, one possible exception to this rule of thumb is a rare phenomenon termed a "meteor storm." Such meteor storms happen on average only once every few decades. The only major meteor storm of the early space age happened on November 17, 1966, when the Leonid meteor shower rained over western North America, providing spectators with a once-in-a-lifetime sight of up to tens of thousands of visible meteors in less than an hour.

Although the number of meteoroids potentially hitting spacecraft spikes during a meteor storm, an additional potential danger exists in the speed of shower meteors, which tend to be many times faster than the average sporadic meteor. The Leonids, traveling at 71 km/s, are near the top of this scale, with other potential storm-producing showers like the Perseids (60 km/s) and Lyrids (43 km/s) also packing a substantial punch. The added velocity is a danger to spacecraft, not only for the added mechanical impact damage produced, but also because, at such high speeds, large amounts of plasma can be produced, which can damage sensitive spacecraft electronics.

No similar storms were seen or expected after the 1966 Leonids until 1993. In 1992, the possibility of a storm from the well-known Perseid meteor shower became a sudden and real possibility with the surprise discovery of the Perseid parent comet, 109P/Swift-Tuttle, as it passed through the inner solar system. The prospect of a substantial storm the following year led to the reorientation of the Hubble Space Telescope near the time of the predicted storm peak and to a delay in the launch of space shuttle mission STS-51. The 1993 shower resulted in a strong surge in meteor numbers but fell short of a storm. Nevertheless, the Olympus telecommunication satellite suffered an impact, likely from a small Perseid meteoroid at the height of the shower, which ultimately led to the termination of that mission.

After the experience of the 1993 Perseid shower and the Olympus impact, the space community became sensitive to the impact damage possibly associated with meteor storms. The Perseids proved a warm-up for the much more spectacular returns of the Leonids, which produced a strong shower in 1998 and true meteor storms in 1999, 2001, and 2002. Several major research efforts recorded the Leonid storms using video cameras and radars, some providing Leonid meteor numbers in real-time to space operators—the first real-time meteoroid "weather" reports. Many satellites were turned to present a minimal target area to the oncoming stream, and several satellite operators took additional precautions, such as turning off high-power subsystems at the time of the predicted peak and ensuring that extra ground support was available in case of an emergency. While major satellite damage did not occur during any of the Leonid storms, in part perhaps because so many satellites took precautions during the height of the storm periods, some smaller anomalies were reported by operators, which have been linked to the sudden increase in numbers of small, fast Leonids.

In the short term, the 2011 October Draconids are predicted by some forecasters to produce a possible strong shower (or maybe even a storm) on October 8, 2011, which is likely to be the last meteor storm for at least a decade.

properties (mass, bulk density).[5] In addition to ground-based observations of meteors, direct in situ measurements are also made by means of space-borne dust detectors, analysis of the surfaces of returned spacecraft, and laboratory measurements of a select suite of meteoroids in the form of airborne collected interplanetary dust particles (IDPs). In situ measurements must also be modeled and calibrated for proper interpretation of the impact signal.

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[5] For example, see S. Close, M. Oppenheim, S. Hunt, and A. Coster, A technique for calculating meteor plasma density and meteoroid mass from radar head echo scattering, *Icarus* 168:43-52, 2004, available at http://soe.stanford.edu/pubs/Icarus_scattering_sigridclose_5373.pdf; J. Borovička, Physical and chemical properties of meteoroids as deduced from observations, pp. 249-271 in *Proceedings of the International Astronomical Union*, Vol. 1, Cambridge University Press, Cambridge, U.K., 2005.

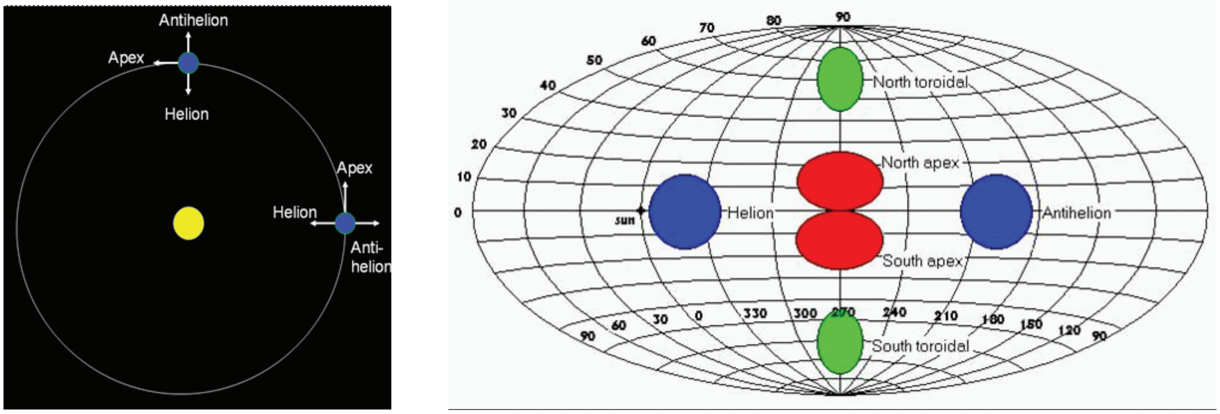

FIGURE 4.1 (*Left*) The diagram shows Earth in orbit about the Sun as seen from the north pole of the ecliptic together with the ram direction (apex of Earth's way) and the Sun (helion) and anti-Sun (antihelion) directions. (*Right*) The same coordinate system (termed the "Sun-centered ecliptic") as seen from the vantage point of Earth looking outward, showing the apex of Earth's way in the center of the plot, the Sun direction (at 0,0), and the anti-Sun direction (180,0). The circles represent the major sporadic meteor sources—i.e., areas on the sky where major concentrations of meteor radiants are present throughout the year.

The meteoroid hazard to spacecraft takes the form of hypervelocity impacts of solid meteoroid particles onto spacecraft surfaces. The character of these impacts differs in several important respects, as compared to impacts from space debris.[6] The average collisional velocity with meteoroids is higher than with orbital debris (in extreme cases, an order of magnitude higher), and the bulk density of meteoroids is typically quite different from that of space debris. Studies of the expected impact damage from meteoroids have tended to focus on mechanical effects and penetration, which is the main damage modality for space debris.[7] However, there is growing evidence that higher-velocity meteoroid collisions may produce plasma, generation of which in the vicinity of an impact may be more damaging in some cases than the purely mechanical effects.[8] This electrical damage can occur in the form of electrostatic discharges or electromagnetic pulses resulting from the direct ionization of the meteoroid and part of the spacecraft.[9]

Many ground-based experiments have shown that plasma is generated by hypervelocity impacts.[10] With respect to electrical effects, meteoroid velocity is the dominant factor, with the amount of charge generated typically scaling as mass times velocity to the fourth power.[11] At least two spacecraft have suffered electrical anomalies that might potentially have been caused by meteoroid impacts during Perseid meteor shower enhancements, including the Olympus satellite in 1993 (Box 4.2) and the Landsat-5 satellite in 2009.[12,13] Such anomalies are difficult to understand in connection with meteor showers, however, since current research suggests that the particle popula-

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[6] M. Landgraf, R. Jehn, W. Flury, and V. Dikarev, Hazards by meteoroid impacts onto operational spacecraft, *Advances in Space Research* 33:1507-1510, 2003.

[7] For example, see E.L. Christiansen, *Handbook for Designing MMOD Protection*, NASA TM-2009-214785, NASA Johnson Space Center, Houston, Tex., 2009.

[8] D.R. Caswell, N. McBride, and A. Taylor, Olympus end of life anomaly—A Perseid meteoroid impact event?, *International Journal of Impact Engineering* 17:139-150, 1995.

[9] G. Drolshagen, Impact effects from small size meteoroids and space debris, *Advances in Space Research* 41:1123-1131, 2008.

[10] J. McDonnell, Microparticle studies by space instrumentation, pp. 337-426 in *Cosmic Dust* (J. McDonnell, ed.), John Wiley and Sons, New York, N.Y., 1978.

[11] J. McDonnell, N. McBride, S. Green, P.R. Ratcliff, D.J. Gardener, and A.D. Griffiths, Near Earth environment, pp. 161-231 in *Interplanetary Dust* (E. Grun, B.A.S. Gustafson, S.F. Dermott, H. and Gechtig, H. eds.), Springer, New York, N.Y., 2001.

[12] Caswell et al., *International Journal of Impact Engineering,* 1995.

[13] W.J. Cooke, *The 2009 Perseid Meteoroid Environment and Landsat 5*, NASA MEO Internal Report, NASA Marshall Space Flight Center in Huntsville, Ala., 2009.

BOX 4.2
Olympus Spacecraft Failure

The Olympus spacecraft was a European Space Agency (ESA) experimental communications satellite that experienced multiple anomalies on August 11, 1993, near the peak of the Perseid meteor shower that year. Olympus lost Earth-pointing attitude and began spinning out of control after having been in orbit for 5 years. A previous temporary loss of the satellite in 1991 had required use of a large amount of fuel for recovery, and when ESA tried to recover the satellite in August 1993, the satellite used up most of its remaining fuel trying to reorient itself, thus making it impossible for the agency to reestablish service and forcing ESA to terminate operations and remove Olympus from geostationary orbit.[1]

Scientists and engineers cannot overlook the possible connection between the timing of this failure and the peak of the Perseid meteor shower, even though the failure occurred 3.5 hours prior to the peak of the Perseid storm. A team composed of specialists from ESA and industry (led by British Aerospace, the prime contractor for Olympus) conducted an investigation into the causes of the anomalies and the ultimate loss of Olympus.[2] The team could not conclusively identify causes of the anomalies that occurred in some of Olympus's systems. An internal electrical anomaly or a meteoroid impact generating a plasma, which then entered the spacecraft, were identified as possible failure modes. Based on the limited data available, the investigation report concluded that "although it was impossible to prove that the demise of Olympus was caused by the impact of a Perseid meteoroid, it does seem probable."[3]

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[1] European Space Agency, "Olympus: End of Mission," Press Release No. 40-1993, available at http://www.esa.int/esaCP/Pr_40_1993_p_EN.html, 1993.

[2] R. Douglas Caswell, Olympus end of life anomaly—A Perseid meteoroid impact event? *International Journal of Impact Engineering* 17:139-150, 1995.

[3] Ibid., p. 149.

tion in showers includes far fewer small meteoroids than does the sporadic background.[14] One possibility is that these impacts are related to natural debris produced by the near-Earth breakup of larger, fragile meteoroids in the stream, a mechanism first suggested as an explanation for the apparent impact clustering detected by the HEOS 2 dust experiment.[15] Furthermore, such small meteoroids can be a particular threat to certain types of space-based sensors (such as focal-plane charge-coupled device sensors in x-ray telescopes), for which at least two impacts have been documented.[16] Impact effects from small meteoroids remain a topic for future investigation, but the need to better characterize meteoroids with high velocities, even if the mass cut-off is below that needed for mechanical damage, is apparent.

DETECTION AND MONITORING

The primary methods for estimating the overall meteoroid flux, velocity, and physical properties of meteoroids include ground-based radar and optical measurements of meteors, in situ impact detections of meteoroids (including detections on returned surfaces), zodiacal brightness measurements, and IDP studies.

In situ measurements include satellite dust detectors on interplanetary spacecraft and on Earth-orbiting satellites. There are several different types of detectors, such as (1) polyvinylidene fluoride (PVDF), which produces a current signal (for meteoroids of mass greater than 10^{-12} grams); (2) penetration detectors (for meteoroids of mass

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[14] J. McDonnell et al., *Interplanetary Dust*, 2001.

[15] H. Fechtig, E. Grün, and G. Morfill, Micrometeoroids within ten Earth radii, *Planetary and Space Science* 27:511-531, 1979, available at http://www.sciencedirect.com/science/article/pii/0032063379901284.

[16] J.D. Carpenter, A. Wells, A.F. Abbey, and R.M. Ambrosi, Meteoroid and space debris impacts in grazing-incidence telescopes, *Astronomy and Astrophysics* 483(3):941-947, 2008.

greater than 10^{-9} grams); (3) microphones that record the momentum transferred to the detector (for meteoroids of mass greater than 10^{-12} grams); (4) ionization detectors that measure the charge produced upon impact (for meteoroids of mass greater than 10^{-15} grams); and (5) return surfaces such as lunar microcraters and spacecraft surfaces. Note that for many of these techniques the speed of individual particles is not known but is usually assumed to be ~20 km/s based on findings about mean speed from earlier radar and optical meteor measurements. More recently published estimates of meteoroid speed using high-power large-aperture radars (HPLA), however, are at variance with such low average velocities (of ~20 km/s).[17,18] Recently proposed in situ dust detection systems offer the prospect of precise measurements of velocity and better measurements of mass on very small individual meteoroids.[19]

Many of these methods preclude decoupling mass from velocity, and others involve a large error associated with the derived measurement. Due to limited collecting area, in situ measurements detect only the smallest meteoroids, since the number of meteoroids follows a power-law distribution. Finally, a very limited amount of meteoroid in situ impact data exists from outside Earth's orbit, resulting in large levels of uncertainty in the meteoroid distribution (particularly at larger sizes) beyond Earth. The inherent difficulty in interpreting in situ data, particularly when speed is not known, can result in great uncertainty in the measurements.[20]

Optical measurements include video and photographic observations of meteors. The primary information extractable from optical measurements pertaining to the general meteoroid environment includes flux and velocity distributions. With significant modeling (and assumptions), both mass and density can be inferred. The main limitation in utilizing optical measurements is characterizing luminous efficiency (the fraction of total initial energy converted into radiation in the instrument passband) in order to relate instrument magnitude to meteoroid mass. Additional instrument biases inherent in the system also have to be removed.[21]

Ground-based radars transmit electromagnetic waves that scatter from the meteor plasma and return to the radar to be interpreted in the form of signal-to-noise ratio (SNR) or radar cross section (RCS). To measure the head plasma for smaller meteoroids, high-power instruments are generally needed because the scattered signal is weak. To measure a trail plasma, either the meteoroid must be traveling in a direction perpendicular to the line-of-sight of the radar (a "specular" trail), or the radar beam must be quasi-perpendicular to the background magnetic field (a "non-specular" trail). Trail data also exhibit a "height ceiling" effect: an altitude cut-off exists, above which a specular radar cannot detect trails as the meteor trail radius approaches the wavelength of the radar, leading to destructive scattering of the reflected wave. Since small, high-velocity meteoroids tend to ablate and form meteors at higher altitudes, there is a subset of high-velocity meteoroids that are notably difficult to detect with "specular-scattering" radars. A similar phenomenon may exist with respect to head echo data, although this is currently an area of active research. Additional uncertainties result when attempts are made to correlate observed meteor parameters with inferred meteoroid properties, such as quantifying the ionization efficiency. All of these unknowns result in a large number of biases associated with radar meteor observations.

Measurements of the meteoroid flux both in situ and from atmospheric observations have been reported for many decades. Figure 4.2 summarizes recent meteoroid flux measurements in the size range of interest for mechanical hazards and includes attempts to remove inherent observational biases. Note that different sources use different assumptions to derive flux; in particular, different average velocities and differing means of converting from observed quantities to mass. Much uncertainty remains in all of these conversions.[22] Among the factors that remain only partly characterized for radar instruments, for example, is understanding the role of magnetic field

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[17] D. Janches, C.J. Heinselman, J.L. Chau, and A. Chandran, Modeling the global micrometeor input function in the upper atmosphere observed by high power and large aperture radars, *Journal of Geophysical Research* 111:A07317, 2006, available at http://www.cora.nwra.com/~diego/2006JA011628.pdf, accessed July 14, 2011.

[18] D. Janches and J.L. Chau, Observed diurnal and seasonal behavior of the micrometeor flux using the Arecibo and Jicamarca radars, *Journal of Atmospheric and Solar-Terrestrial Physics* 67:1196-1210, 2005, available at http://www.cora.nwra.com/~diego/Janches-Chau.pdf, accessed July 14, 2011.

[19] Z. Sternovsky et al., "Novel instrument for Dust Astronomy: Dust Telescope," Aerospace Conference, 2011 IEEE, pp. 1-8, March, 5-12, 2011, doi: 10.1109/AERO.2011.5747300.

[20] McDonnell, *Cosmic Dust,* 1978.

[21] Z. Ceplecha, J. Borovička, W.G. Elford, D.O. ReVelle, R.L. Hawkes, V. Porubčan, and M. Šimek, Meteor phenomena and bodies, *Space Science Reviews* 84:327-471, 1998, available at http://www.springerlink.com/content/r2602605vm031517/, accessed July 14, 2011.

[22] For a review, see Ceplecha et al., *Space Science Reviews,* 1998.

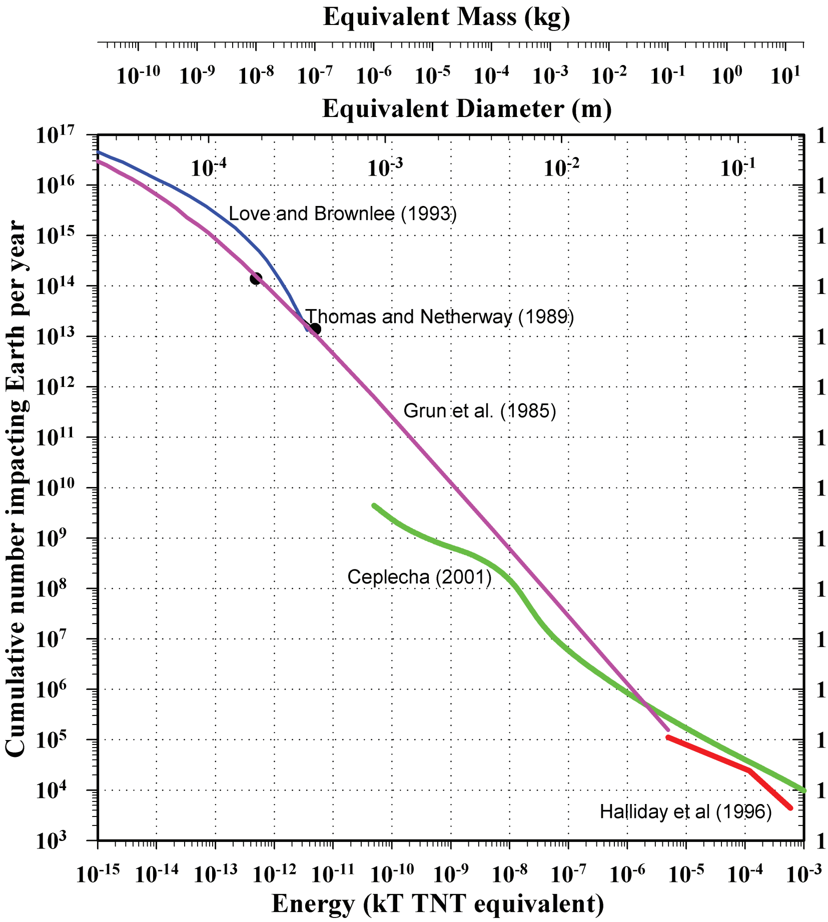

FIGURE 4.2 Flux of meteoroids at the top of Earth's atmosphere as reported by various authors. Grün et al. (1985) is a compilation of in situ and meteor measurements made prior to the mid-1980s. Love and Brownlee (1993) reflects flux values derived from the returned surface of the Long Duration Exposure Facility. Thomas and Netherway (1989) describes meteoroid fluxes measured by a low-frequency over-the-horizon radar, while Ceplecha (2001) is a compilation of optical meteor measurements using recently reported values for the luminous efficiency. Halliday et al. (1996) is a determination of fireball fluxes as measured by the Meteorite Observation and Recovery Project. SOURCE: Data from E. Grün, H. Zook, H. Fechtig, and R.H. Giese, Collisional balance of the meteoritic complex, *Icarus* 62:244-272, 1985; S.G. Love and D.E. Brownlee, A direct measurement of the terrestrial mass accretion rate of cosmic dust, *Science* 262:550-553, 1993; R.M. Thomas and D.J. Netherway, Observations of meteors using an over-the-horizon radar, *Proceedings of the Astronomical Society of Australia* 8:88-93, 1989; Z. Ceplecha, The meteoroidal influx to the Earth, *Astrophysics and Space Science Library* 261:35-50, 2001; I. Halliday, A.A. Griffin, and A.T. Blackwell, Detailed data for 259 fireballs from the Canadian camera network and inferences concerning the influx of large meteoroids, *Meteoritics and Planetary Science* 31:185-217, 1996.

effects, polarization properties, radar frequency, initial trail radius, and ionospheric effects on biases, while for optical instruments a major uncertainty involves meteor spectral energy distribution. The conversion of meteor brightness or radar cross section to equivalent mass, in particular, has a wide range of proposed forms as a function of velocity and mass, used variously in the literature.

Another cornerstone of all meteoroid environment models is the meteoroid velocity distribution at Earth. Most models use either the Harvard Radio Meteor Project radar-derived velocity distribution[23] or the distribu-

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[23] A.D. Taylor, The Harvard radio meteor project meteor velocity distribution reappraised, *Icarus* 116:154-158, 1995.

tion derived from super-Schmidt optical measurements from the Harvard meteor program (including the Harvard Photographic Meteor Program and the Harvard Radio Meteor Program).[24,25] No statistically significant in situ velocity measurements have yet been made for meteoroids.[26] More recent measurements using radial scattering from head echoes as detected by high-power, large-aperture radar extending to very small masses suggest a very different (and much higher) speed distribution than is derived from the earlier estimates.[27] As shown in Figure 4.3, the mass-limited velocity distribution shows wide variation depending on the study; this may reflect a change in the velocity distribution with mass, an effect predicted by numerous authors,[28] or result from instrumentation biases or deficiencies in the models that convert the measured signal of the plasma to meteoroid mass. If strong changes in the velocity distribution with mass are present in the environment, large errors in assessments of damage may occur, including both mechanical and electrical impact effects.

A final major parameter required to interpret meteoroid impact effects is the bulk density of a meteoroid. This is a very difficult quantity to measure; all such measurements are necessarily indirect. Direct measurements of bulk density from recovered IDPs are strongly biased toward IDPs with low entry velocities due to mass-velocity selection effects, which make survivability less likely for high-velocity IDPs.[29] Values for the inferred bulk density of meteoroids from optical measurements coupled to ablation models show systematic differences due, in large part, to differing choices in (largely unconstrained) model parameters and the need to include effects such as meteoroid fragmentation. Similar attempts to derive densities from radar data also exhibit such tendencies. All studies, however, suggest that the true distribution in densities covers a wide range (more than an order of magnitude).[30]

Finding: The models used to relate measurements of plasma to fundamental parameters of a meteoroid contain large uncertainties and errors. These models include, but are not limited to, electromagnetic scattering models, luminous emission models, and meteoroid fragmentation models.

Finding: Because the scientific community infers the properties of a meteoroid indirectly from its effects on the atmosphere (a meteor) or the effects of its impact on a spacecraft, it is imperative to understand observational biases inherent in each instrument that affect the detection of these secondary effects.

MODELING AND SIMULATION

The meteoroid hazard to a spacecraft can be estimated in a probabilistic manner by knowing (1) the flux of meteoroids above some specified size or mass, (2) the velocity distribution of the impacting population, (3) the bulk density of the impacting meteoroids, and (4) the directionality of the meteoroid flux relative to a spacecraft surface. In addition, in order to understand the hazard as it relates to electrical damage, it is important to know (1) the spacecraft material properties, including surface potential, and (2) the proximity of electrical components and shielding relative to impact location. These considerations are commonly bundled in a single environment model and, when combined with a model for impact damage (i.e., a BUMPER-like model), provide a specific estimate for spacecraft mechanical damage given a known spacecraft orbit.

The dominant parameters for assessing mechanical damage are meteoroid mass and velocity, whereas the primary parameter for assessing electrical damage is velocity. It is therefore crucial that small, fast meteoroids be considered, even if the mass threshold lies below that needed to produce mechanical damage.

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[24] J.E. Erickson, Velocity distribution of sporadic photographic meteors, *Journal of Geophysical Research* 73:3721-3726, 1968.

[25] D.J. Kessler, Average relative velocity of sporadic meteoroids in interplanetary space, *AIAA Journal*. 7:2337-2338, 1969.

[26] McDonnell et al., *Interplanetary Dust*, 2001.

[27] Janches et al., *Journal of Geophysical Research,* 2006.

[28] See also T.R. Kaiser, Interplanetary dust cloud, pp. 323-342 in *International Astronomical Union Symposium #33: Physics and Dynamics of Meteors* (L. Kresak and P.M. Millman, eds.), Springer-Verlag, New York, 1968; P.A. Wiegert, J. Vaubaillon, and M. Campbell-Brown, A dynamical model of the sporadic meteoroid complex, *Icarus* 201:295-310, 2009.

[29] S.G. Love and D.E. Brownlee, A direct measurement of the terrestrial mass accretion rate of cosmic dust, *Science* 262:550-553, 1993.

[30] J. Borovička, Physical and chemical properties of meteoroids as deduced from observations, pp. 249-271 in *Proceedings of the International Astronomical Union*, Vol. 1, Cambridge University Press, Cambridge, U.K., 2005.

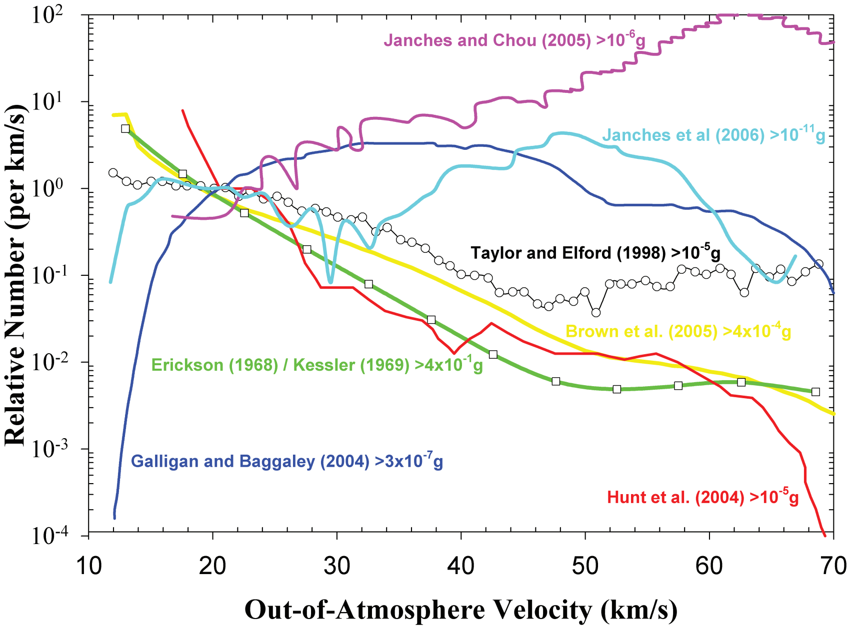

FIGURE 4.3 Meteoroid velocity distributions as reported in the literature for meteors from gram-size ($>4 \times 10^{-1}$ g) to approximate nanogram masses ($>1 \times 10^{-11}$ g) as reported by radar. Data sources for the Harvard Super-Schmidt Photographic data ($>4 \times 10^{-1}$ g; Erickson, 1968; Kessler, 1969), the Advanced Meteor Orbit Radar ($>3 \times 10^{-7}$ g; Galligan and Baggaley, 2004), the Canadian Meteor Orbit Radar ($>4 \times 10^{-4}$ g; Brown et al., 2005), the Harvard Radio Meteor Project ($>1 \times 10^{-5}$ g; Taylor and Elford, 1998), the ARPA Long-Range Tracking and Instrumentation Radar ($>1 \times 10^{-5}$ g; Hunt et al., 2004), the Jicamarca Radio Observatory ($>1 \times 10^{-6}$ g; Janches and Chau, 2005), and the Arecibo Radar ($>1 \times 10^{-11}$ g; Janches et al., 2006). SOURCE: J.E. Erickson, Velocity distribution of sporadic photographic meteors, *Journal of Geophysical Research* 73:3721-3726, 1968; D.J. Kessler, Average relative velocity of sporadic meteoroids in interplanetary space, *AIAA Journal* 7:2337-2338, 1969; D.P. Galligan and W.J. Baggaley, The orbital distribution of radar-detected meteoroids of the Solar system dust cloud, *Monthly Notices of the Royal Astronomical Society* 353(2):422-446, 2004; P. Brown, J. Jones, R.J. Weryk, and M. Campbell-Brown, The velocity distribution of meteoroids at the Earth as measured by the Canadian Meteor Orbit Radar (CMOR), *Earth, Moon and Planets* 95(1-4):617-626, 2005; A.D. Taylor and W.G. Elford, Meteoroid orbital element distributions at 1 AU deduced from the Harvard Radio Meteor Project observations, *Earth Planets Space* 50:569-575, 1998; S.M. Hunt, M. Oppenheim, S. Close, P.G. Brown, F. McKeen, and M. Minardi, Determination of the meteoroid velocity distribution at the Earth using high-gain radar, *Icarus* 168:34-42, 2004; D. Janches and J.L. Chau, Observed diurnal and seasonal behavior of the micrometeor flux using the Arecibo and Jicamarca radars, *Journal of Atmospheric and Solar-Terrestrial Physics* 67:1196-1210, 2005; and D. Janches, C.J. Heinselman, J.L. Chau, and A. Chandran, Modeling the global micrometeor input function in the upper atmosphere observed by high power and large aperture radars, *Journal of Geophysical Research* 111:A07317, 2006.

There are two contemporary NASA meteoroid models in use today: NASA SSP 30425, developed in the late 1980s and early 1990s primarily to address the issue of meteoroid damage to the space station,[31] and the NASA Meteoroid Environment Model.[32] Both models use as their flux reference the Grün et al. Interplanetary Flux Model (Grün IFM).[33]

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[31] B.J. Anderson and R.E. Smith, *Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development,* NASA TM-4527, NASA, June 1994, available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19940031668_1994031668.pdf, accessed August 16, 2011.

[32] H. McNamara, R. Suggs, J. Jones, W. Cooke, and S. Smith, Meteoroid Engineering Model (MEM): A meteoroid model for the inner solar system, *Earth, Moon, and Planets* 95:123-139, 2004, available at http://www.nasa.gov/pdf/195790main_McNamara_04-MEM.pdf, accessed August 16, 2011.

[33] E. Grün, H. Zook, H. Fechtig, and R.H. Giese, Collisional balance of the meteoritic complex, *Icarus* 62:244-272, 1985.

The Grün IFM[34] is an empirical compilation of many sources of data and is used as the standard reference for meteoroid flux in near-Earth space. It is based on in situ dust detector fluxes from missions prior to the mid-1980s, lunar microcratering, measurements of zodiacal brightness, and early measurements of meteor flux. The IFM ignores the directionality in the sporadic meteoroid flux and uses a mean velocity (rather than a velocity distribution) in computing flux values. It also ignores temporal variations in the background sporadic meteoroid flux, which have been measured as having an amplitude near a factor of 2 throughout the year.[35] For masses of less than 100 μm the IFM is well validated by numerous (and varied) sources of data. Recent (after the mid-1980s) meteoroid flux measurements have been found to be in general agreement with the Grün curve within uncertainty bounds applying at these smaller masses. However, for meteoroids with larger masses, order-of-magnitude disparities exist (see Figure 4.2). At sizes greater than 0.1 mm, fluxes can be derived only from meteor data, and the large uncertainty in mass-brightness-velocity conversions between earlier data and more recent measurements has become apparent.

The SSP 30425 meteoroid model uses as its basis the Grün IFM but makes assumptions about the velocity distribution that are incompatible with the velocity assumptions in the IFM. This inconsistency results in a roughly factor-of-2 underestimation of the flux relative to the IFM (which is the input to SSP 30425). This result is independent of the uncertainty in the flux caused by uncertainty in derived meteoroid mass from measurements, which produces an additional error factor of approximately 3 at submicrogram masses.[36] SSP 30425 also assumes isotropy in impact directions, which is at variance with observations.[37] The meteoroid bulk density distribution used in SSP 30425 incorporates estimates guided by early radar and photographic measurements of bulk density and chosen to vary as a function of mass from 2 g/cm^3 for mass less than 10^{-6} g, to 1 g/cm^3 for mass between 10^{-6} and 10^{-2} g, and 0.5 g/cm^3 for mass greater than 10^{-2} g,[38] although the actual variation in bulk density has been shown to correlate strongly with orbit type rather than mass alone.[39]

A physics-based model, the Meteoroid Environment Model (MEM) starts with an assumed parent source population (comets and asteroids) and propagates released meteoroids forward in time in a Monte Carlo manner until they encounter Earth. This distribution of Earth-impacting particles is calibrated in its directionality and velocity distribution by radar measurements and adopts the IFM for flux.[40] It has several variants (see Table 3.1 in Chapter 3) but includes Earth-shielding and gravitational focusing where appropriate, and it adopts a single meteoroid density of 1 g/cm^3 to provide compatibility in final flux values with the IFM, given the difference in mean velocity between MEM and the IFM. Validation for MEM has come only from data from near-Earth space, while the Grün IFM (implicitly used in MEM) provides meteoroid flux at 1 AU. Although some in situ measurements of very small meteoroids, together with measurements of zodiacal light, provide limited data on meteoroid populations at other heliocentric distances, much greater uncertainties exist in the measurements of meteoroid flux at distances other than 1 AU, with contradictory results particularly evident in measurements in the outer solar system.[41] Confident extension of MEM to other heliocentric distances and larger particle sizes likely will require additional measurements beyond those that exist at present.

Recently published work offers the prospect of a higher-fidelity evolutionary model of sporadic meteoroids,[42] although such newer work does not entirely agree on source populations and their relative strengths. Development of more physically realistic meteoroid models that fit the available constraints from all data sources remains to be done.

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[34] Grün et al., *Icarus,* 1985.

[35] M. Campbell-Brown and J. Jones, Annual variation of sporadic radar meteor rates, *Monthly Notices of the Royal Astronomical Society* 367:709-716, 2006, available at http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2966.2005.09974.x/pdf, accessed August 16, 2011.

[36] Anderson and Smith, *Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development,* 1994.

[37] Jones and Brown, *Royal Astronomical Society, Monthly Notices,* 1993.

[38] Anderson and Smith, *Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development,* 1994.

[39] Ceplecha et al., *Space Science Reviews,* 1998.

[40] McNamera et al., *Earth, Moon, and Planets,* 2004; Jones and Brown, *Royal Astronomical Society, Monthly Notices*, 2003.

[41] C. Leinert and E. Grün, Interplanetary dust, pp. 207-282 in *Physics of the Inner Heliosphere II* (R. Schewenn and E. Marsch, eds.), Springer-Verlag, Berlin, Germany, 1990.

[42] See Wiegert et al., *Icarus,* 2009; D. Nesvorny, P. Jenniskens, H.F. Levison, W.F. Bottke, D. Vokrouhlický, and M. Gounelle, Cometary origin of the zodiacal cloud and carbonaceous micrometeorites: Implications for hot debris disks, *Astrophysical Journal* 713:816-836, 2010.

Finding: The Meteoroid Environment Model incorporates in its predictions the latest available data on the meteoroid environment, including the directionality and full velocity distribution of the meteoroids. It is currently the NASA model that is most consistent with the known meteoroid environment, although some major uncertainties still remain.

Recommendation: The NASA meteoroid and orbital debris programs should establish a baseline effort to evaluate major uncertainties in the Meteoroid Environment Model regarding the meteoroid environment in the following areas: (1) meteoroid velocity distributions as a function of mass; (2) flux of meteoroids of larger sizes (>100 microns); (3) effects of plasma during impacts, including impacts of very small but high-velocity particles; and (4) variations in meteoroid bulk density with impact velocity.

Finding: The earlier SSP 30425 meteoroid model does not reproduce existing observational meteoroid data with a fidelity equal to that of the Meteoroid Environment Model. Numerous disparate sources of data have been fused to produce the current meteoroid flux model used by NASA, sometimes incorporating differing underlying assumptions.

Finding: The Meteoroid Environment Model currently does not extend to prediction of the meteoroid environment in the outer solar system, and the measurements it incorporates are poorly constrained in the cis-martian region.

Recommendation: An effort should be made to re-examine earlier data used in the Grün Interplanetary Flux Model and to reconcile the data with more recent measurements in the literature on meteoroid flux, and a technical evaluation should be undertaken to synthesize and document such data as it is incorporated into the Meteoroid Environment Model (MEM). Updates of the MEM and technical development should follow a technical pathway as rigorous as that being taken for updates of the Orbital Debris Environment Model.

Recommendation: NASA should adopt the Meteoroid Environment Model for agency-wide official use and extend its capabilities to the outer solar system.

5

Risk Assessment and Uncertainty

A number of risk assessment and uncertainty concepts are used in very different ways by different analysts, so the following definitions are offered to clarify the committee's use of terms: *hazards* refer to threats to people and the things they value (such as ecosystems, security, or mission success in space),[1] *risk* is the probability that a particular event or activity will result in a specified consequence,[2] and *uncertainty* refers to the lack of knowledge and understanding of the structure of a risk and the connections between the stages of risk evolution. Ideally, if certainty is high, the connections among risk stages can be characterized quantitatively. A full risk assessment should always provide not only estimates of risk but also estimates of the associated uncertainties.[3] Uncertainties can arise from different sources, such as data inadequacies, model parameters, or lack of scientific understanding of the phenomena. Evaluating the type and source of uncertainty and the ability to reduce it through further research and experience is an important part of any risk analysis.

RISK ASSESSMENT

Overall risk is typically assessed via a probabilistic risk assessment (PRA). In essence, a PRA attempts to determine the overall risk associated with a particular program or a mission stage by factoring in all known risks, and their corresponding uncertainties, if known. The threat to mission success and human life from the meteoroid and orbital debris (MMOD) environment is one of the risks to be considered within a PRA. In its most general sense, a PRA is a systematic approach to providing quantitative answers to the following fundamental safety questions:

- What can go wrong? (What are the scenarios?)
- How likely is it to happen? (What is the frequency of each scenario?)
- What are its consequences? (i.e., of each scenario)
- What is the uncertainty associated with the state of knowledge regarding these answers?[4]

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[1] R. Kates, C. Hohenemser, and J.X. Kasperson, eds., *Perilous Progress: Managing the Hazards of Technology*, Westview, Boulder, Colo., 1985.

[2] Kates et al., *Perilous Progress: Managing the Hazards of Technology*, 1985.

[3] National Research Council, *Science and Decisions: Advancing Risk Assessment*, The National Academies Press, Washington, D.C., 2009, available at http://books.nap.edu/catalog.php?record_id=12209.

[4] S. Kaplan and B.J. Garrick, On the quantitative definition of risk, *Risk Analysis* 1:11-37, 1981, available at http://josiah.berkeley.edu/2007Fall/NE275/CourseReader/3.pdf.

Before the *Challenger* accident in 1986, NASA management did not encourage or seem to understand the use of PRA, as reflected by the accident investigator and Nobel laureate Richard Feynman's statement, "It appears that there are enormous differences of opinion as to the probability of a failure with loss of vehicle and of human life. The estimates range from roughly 1 in 100 to 1 in 100,000. The higher figures come from the working engineers, and the very low figures from management."[5] After the *Columbia* shuttle accident, the accident investigation board again urged NASA to enhance its risk analyses.[6] This lack of attention to probabilistic risk assessment by NASA management had resulted in the MMOD programs finding it difficult to become part of any overall risk assessment associated with mission design and operations, since there was no agreed upon procedure for doing so. This is less true today: NASA management has become increasingly aware of the necessity for risk management, as reflected in NRC studies concerning MMOD with regard to the space shuttle[7] and the International Space Station (ISS).[8]

The initial goals of NASA's MMOD efforts were to characterize the risk to humans in space, beginning with NASA's crewed spacecraft programs, more than 50 years ago.[9] The primary tool for characterizing risk has been what could be called a Poisson Consensus Model,[10] which has the purpose of consolidating theory, measurements, and assumptions into an average event rate where Poisson statistics apply. This approach requires the integration of various statistical distributions (such as velocity and angle of impact) by techniques that were established early in the MMOD programs.[11] The history of these consensus models predates the beginning of the space program,[12] and they have since been used and their accuracy improved over the years by the international community.

Over time, NASA's efforts have expanded to include the characterization of risk to uncrewed spacecraft and the addition of the orbital debris population as another source of risk. This addition quickly led to the conclusion that risk could be reduced by minimizing the growth in the orbital debris population. In addition, just as international interest has increased in minimizing the risk to Earth from natural collisions with comets and asteroids, the NASA MMOD programs have also expanded to minimize the risk to people and assets on the ground from reentering orbital debris. As a result of the 2010 National Space Policy,[13] which directs NASA to consider the issues involved in the active removal of large derelict debris from orbit, the goal of minimizing risk on the ground is likely to have increasing priority, and trade-offs between reducing the risks to Earth and the risks to spacecraft in orbit may be required. In addition, the risk posed by MMOD has now expanded to include the possibility of catastrophic damage to a spacecraft resulting from colliding with a tracked object in orbit. Other changes to NASA's mission could occur in the future, for which NASA may need to be prepared.

The hazard from the MMOD environment represents only one component of the total risk to any system or program. It is up to NASA's program managers to identify systems critical to their mission and manage the risk to those systems. The responsibilities of MMOD programs include determining the probability of failure of any critical system as a result of being hit by either a meteoroid or orbital debris object. Failure for crewed critical systems is defined as loss of the vehicle or loss of life. In some cases what constitutes failure is obvious, such as the penetration of a pressurized container. In other cases a cause of failure is not as obvious; examples include events that could lead to an electrical failure and be interpreted as such (for example, spraying high-speed ejecta

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[5] R.P. Feynman, Personal observations on reliability of shuttle, Appendix F in *Report of the PRESIDENTIAL COMMISSION on the Space Shuttle Challenger Accident*, Volume 2, June 6, 1986, available at http://history.nasa.gov/rogersrep/v2appf.htm.

[6] Columbia Accident Investigation Board, History as cause: Columbia and Challenger, Chapter 8 in *Columbia Accident Investigation Board Report*, Vol. 1, NASA, August 2003, available at http://www.sociology.columbia.edu/pdf-files/vaughan5.pdf

[7] National Research Council, *Protecting the Space Shuttle from Meteoroids and Orbital Debris*, National Academy Press, Washington, D.C., 1997, available at http://www.nap.edu/catalog.php?record_id=5958.

[8] National Research Council, *Protecting the Space Shuttle from Meteoroids and Orbital Debris*, 1997.

[9] B.G. Cour-Palais, with the assistance of an ad hoc committee, *Meteoroid Environment Model¾1969 (Near-Earth to Lunar Surface), NASA Space Vehicle Design Criteria (Environment),* NASA SP-8013, March 1969, available at http://www.spaceflightnews.net/special/sp8000/archive/00000012/01/sp8013.pdf.

[10] M. Drouin, G. Parry, J. Lehner, G. Martinez-Guridi, J. LaChance, and T. Wheeler, *Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decisions Making,* NUREG-1855, Vol. 1, U.S. Nuclear Regulatory Commission, March 2009.

[11] D. Kessler, *A Guide to Using Meteoroid-Environmental Models for Experiment and Spacecraft Design Applications,* NASA TND-6596, NASA, March 1972.

[12] A.C. Lovell, *Meteor Astronomy*, Oxford University Press, Oxford, U.K., 1954.

[13] *National Space Policy of the United States of America*, June 28, 2010, available at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf, accessed July 6, 2011.

over a circuit board, severing an electrical wire, or creating a plasma). In these more complex failures, additional hypervelocity testing may be required to determine failure mechanisms.

A solution to reducing failure rates from such collisions can be to add shielding, which sometimes must be customized to minimize the added weight to the spacecraft. Where uncertainty exists, safety factors are sometimes added. In other cases, the risk can be reduced by redundant systems or changes in operations, such as orienting the spacecraft in a direction that minimizes the risk (as has been done for the space shuttle).

It is the responsibility of the MMOD programs, usually through the Hypervelocity Impact Technology Facility, to coordinate with the program managers and offer the best solutions for their mission. The MMOD programs have put together a handbook to aid in selecting spacecraft protection options.[14] As stated in the handbook, the definition of "failure" has a significant influence on the resulting risk. For example, failure may be defined as a penetration of a critical item that could lead to either loss of the function of the item, or loss of the crew. Such a definition could lead to a significant amount of hypervelocity testing and shielding development, as was the case for the critical items identified for the ISS.[15] Alternatively, the failure criterion could be as simple as the depth of the pits on a window pane that might lead to loss of the window during launch, which was one of the critical items identified for the space shuttle.[16] In this case a sufficient amount of hypervelocity testing had already been conducted to identify the frequency with which such pits would occur, and all that was then necessary was to operationally plan to examine the windows after each flight and have enough spare windows on hand as replacements when craters were found that exceeded the critical depth.

The focus on collisions and risk from penetration does not, however, fully cover all of the risks involving orbital debris and interplanetary meteoroids. Other risks are discussed more fully in other chapters. In some cases the difficulty in assessing risk is not the result of poor analysis but is the result of lack of data; for example, as is pointed out in Chapter 4, the risk analysis to be performed is sound but suffers from the lack of measurements in the interplanetary environment.

Finding: NASA's MMOD risk assessment processes have evolved beyond focusing primarily on the damage to spacecraft from collisions with debris that are too small to track, to incorporating a more complete range of risks. More remains to be accomplished, however, including the need in some cases for more measurements as parameters for risk analyses. As gaps are filled, NASA's MMOD efforts can progress toward ever more integrative risk assessment in which all sources and types of risk are modeled and assessed.

Recommendation: Although NASA should continue to allocate priority attention and resources to collision risks and conjunction analysis, it should also work toward a broad integrative risk analysis to obtain a probabilistic risk assessment of the overall risks present in the MMOD domain in which all sources of risk can be put in context.

UNCERTAINTY

Communication of Information About Uncertainty

NASA's work on reducing the threat to spacecraft posed by orbital debris and meteoroids faces increasingly challenging problems stemming from the complexity of physical changes in space, changing spacecraft designs, increased international use of space and contributions to debris, and private and public sector initiatives in space. An intrinsic challenge also exists in creating models that fully capture the uncertainties and the phenomena being modeled. Examining the sources of the uncertainties, how to reduce uncertainties, identifying those that cannot

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[14] E. Christiansen, J. Arnold, A. Davis, D. Lear, J.-C. Liou, F. Lyons, T. Prior, M. Ratliff, S. Ryan, F. Giovane, B. Corsaro, and G. Studor, *Handbook for Designing MMOD Protection,* NASA TM-2009-214785, NASA, June 2009.

[15] E. Christiansen, K. Nagy, D. Lear, and T. Prior, Space station MMOD shielding, *Acta Astronautica* 65(7-8):921-929, 2009.

[16] K. Edelstein, *Orbital Impacts and the Space Shuttle Windshield,* NASA-TM-110594, NASA, Washington, D.C., 1995.

be significantly reduced or removed over the near term, and estimating the time and effort required to significantly reduce extant uncertainties are also issues that need to be addressed. It must also be understood that natural variabilities in the MMOD environment will prevent uncertainties from being removed entirely, no matter how sophisticated and detailed testing programs and modeling efforts become. No less a problem is how to then communicate uncertainties to decision makers or the public. Integrating uncertainty analysis into decision making related to debris impact risks has progressed and can make additional progress going forward. Since many decisions are made at the mission level, how to effectively communicate uncertainties to people with little formal training in managing uncertainties is a matter of considerable importance. The state of knowledge of how to characterize, catalog, and communicate the range of uncertainties is an evolving area.

A description of uncertainty is critical to guiding future research efforts, as well as communicating to those who may be affected by the risk. There is a considerable literature on uncertainty and risk more generally.[17] A recent NRC report also captures some of the science of risk and uncertainty.[18] The principles of uncertainty are summarized in Box 5.1 of the present report, and it is recommended that the MMOD programs increase their efforts to adhere to those principles.

Finding: The calculation and communication of information about uncertainty are critical to properly assessing operational alternatives based on calculated risks posed by orbital debris.

Uncertainty in MMOD Modeling

All of the MMOD models contain uncertainties (see, for example, the discussions of uncertainties pertaining to the orbital debris and meteoroid models in Chapters 3 and 4 and BUMPER in Chapter 6). The building of these models requires an examination of uncertainties that result from data, which may result from a number of measurements, tied together with a number of assumptions. In the past, uncertainties that were judged to be large enough to significantly affect spacecraft designs or operations were identified and brought to the attention of the appropriate program manager. This happened in July 1987 when NASA headquarters' senior staff was briefed on the uncertainty in the orbital debris flux due to a lack of measurements of debris in the size range of interest to the then-planned space station. This briefing led to the current Haystack observation program. In July 1993, a briefing to the Shuttle Program Office about the uncertainty of possible damage to the space shuttle during a predicted Perseid meteor storm led to a delay in the STS-51 launch and the beginning of the current meteoroid program at Marshall Space Flight Center. Consequently, it appears that the MMOD programs effectively deal with uncertainty when that uncertainty is either small enough to be ignored or so large that it is obvious that more data are required. However, this approach may not be sufficient going forward. Inadequate consideration of MMOD uncertainties is becoming more important as the program expands, more data are obtained, and safety requirements become tighter. An increased awareness of uncertainty will also be required to adequately respond to various findings in other chapters of this report.

As discussed elsewhere in this report, there is an opportunity to reduce uncertainties in the environment

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[17] See, for example M.G. Morgan and M. Herion, *Uncertainty: A Guide Toward Dealing with Uncertainties in Quantitative Risk and Policy Analysis*, Cambridge University Press, Cambridge, U.K., 1990; National Research Council, *Understanding Risk: Informing Decisions in a Democratic Society* (P.C. Stern and H.V. Fineberg, eds.), National Academy Press, Washington, D.C., 1996; National Science and Technology Council, *Grand Challenges for Disaster Reduction*, Washington, D.C., 2005; National Research Council, *Science and Decisions: Advancing Risk Assessment*, The National Academies Press, Washington, D.C., 2009; National Research Council, *Science and Judgment in Risk Assessment*, National Academy Press, Washington, D.C., 1994; A.M. Finkel, *Confronting Uncertainty in Risk Management: A Guide for Decision Makers*, Center for Risk Management, Washington, D.C., 1990; R.E. Kasperson, Coping with deep uncertainty: Challenges for environmental assessment and decision making, pp. 337-348 in *Uncertainty: Multi-disciplinary Perspectives on Risk* (G. Banner and M. Smithson, eds.), Earthscan, London, U.K., 2008.

[18] National Research Council, *Science and Decisions: Advancing Risk Assessment,* The National Academies Press, Washington, D.C., 2009. *Science and Decisions*, known as the "Silver Book," replaced the "Red Book" (National Research Council, *Risk Assessment in the Federal Government,* National Academy Press, Washington, D.C., 1983).

BOX 5.1
Recommended Principles for Analysis of Uncertainty and Variability

1. Risk assessments should provide a quantitative, or at least qualitative, description of uncertainty and variability consistent with available data. The information required to conduct detailed uncertainty analyses may not be available in many situations.

2. In addition to characterizing the full population at risk, attention should be directed to vulnerable individuals and subpopulations that may be particularly susceptible or more highly exposed.

3. The depth, extent, and detail of the uncertainty and variability analyses should be commensurate with the importance and nature of the decision to be informed by the risk assessment and with what is valued in a decision. This may best be achieved by early engagement of assessors, managers, and stakeholders in the nature and objectives of the risk assessment and the terms of reference (which must be clearly defined).

4. The risk assessment should compile or otherwise characterize the types, sources, extent, and magnitude of variability and of substantial uncertainty associated with the assessment. To the extent feasible, there should be homologous treatment of uncertainty among the different components of a risk assessment and among different policy options being compared.

5. To maximize public understanding of and participation in risk-related decision making, a risk assessment should explain the basis and the results of the uncertainty analysis with sufficient clarity to be understood by the public and decision makers. The uncertainty assessment should not be a significant source of delay in the release of a risk assessment.

6. Uncertainty and variability should be kept conceptually separate in the risk characterization.

measurements, shielding, and modeling programs. Box 5.2 summarizes an example seen in an early publication of the Haystack data which makes use of confidence bars.[19]

However, there is an additional uncertainty in debris size that cannot be quantified with confidence bars and is likely to be more important; this uncertainty is the result of three assumptions: (1) the distribution of the fragment shapes and composition of test samples used to determine debris size from the RCS is assumed to be representative of the distribution of shapes and composition of debris in orbit (see Chapter 2); (2) those shapes and compositions are then assumed to be adequately described by a single parameter known as a "characteristic length"; and (3) these assumptions carry through to the hypervelocity testing, and the program BUMPER, in which the additional assumption is made that the "characteristic length" of a given piece of debris can be approximated with an aluminum sphere of the same diameter (see Chapter 6). The importance of these last two assumptions can be seen by comparing the results of two studies: under the current set of assumptions, shielding is over-designed;[20] but if the debris size had been defined as the *mass* having a given RCS, and that mass were approximated with an aluminum sphere of the same *mass*, the shielding would be under-designed.[21]

However, the assumption that any particular size sphere is an approximation to any assumed or measured distribution of shapes and composition is not supported by an analysis that includes integrating over the distributions of shape and composition.[22] Finally, China's anti-satellite test (see Box 1.2 in Chapter 1) gives reason to question that the assumed distribution of shapes and composition is correct. The area-to-mass ratio of the fragments from

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[19] E.G. Stansbery, G. Bohannon, C. Pitts, T. Tracy, and J. Stanley, Radar observations of small space debris, *Advances in Space Research* 13(8):43-48, 1993.

[20] J. Williamsen, *Review of Space Shuttle Meteoroid/Orbital Debris Critical Risk Assessment Practices*, Report No. P-3838, Institute for Defense Analyses, Alexandria, Va., November 2003.

[21] B. Cour-Palais, The shape effect of non-spherical projectiles in hypervelocity impacts, *International Journal of Impact Engineering* 26:129-143, 2001.

[22] When this type of analysis is performed to relate characteristic size to RCS, it is heavily weighted toward the more numerous smaller objects. Consequently, if such an analysis were applied to relate impact damage to some characteristic size, it might easily be weighted toward smaller, but higher density iron or aluminum oxide debris objects.

BOX 5.2
The Haystack Data

Stansbery et al. illustrate with 99 percent confidence bars that when the number of objects passing through the Haystack field of view is large, as it is for the smaller debris, there is very little uncertainty in the average flux for that diameter debris compared to the uncertainty in flux for larger diameters.[1] However, "diameter" is not directly measured; radar cross section (RCS) is measured and, consequently, there is an uncertainty in the debris diameter corresponding to a given RCS. In considering Bohannon and Caampued, one would expect the diameter uncertainty to also increase with decreasing flux, given that the distribution of possible RCSs for a given diameter is used in a statistical technique to relate RCS to diameter.[2,3] The lack of increasing uncertainty shown in debris diameter indicates there may be a problem with describing the uncertainty in debris diameter. An examination of Bohannon and Caampued[4] reveals the probable cause: only an approximate uncertainty is given, which is acknowledged as "depending on the RCS statistics." After 18 years of observations, those statistics would have reduced both uncertainties considerably. This was illustrated 8 years later at the Third European Conference on Space Debris, when the statistical uncertainty for the smaller, more hazardous size debris had all but disappeared, and assumptions about shape were being tested using radar polarization measurements.[5] Shape and mass still remain a significant cause of uncertainty due to incomplete testing and analysis of all assumptions.

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[1] E.G. Stansbery, G. Bohannon, C. Pitts, T. Tracy, and J. Stanley, Radar observations of small space debris, *Advances in Space Research* 13(8):43-48, 1993.

[2] G. Bohannon and T. Caampued, *Debris Size Estimation from Radar Cross Section Data Using Quadratic and Non-Parametric Classifiers,* XonTech, Inc. Report No. 930301-BE2198, Van Nuys, Calif., June 1993.

[3] G. Bohannon and N. Young, *Debris Size Estimation Using Average RCS Measurements,* XonTech, Inc. Report No. 930781-BE2247, Van Nuys, Calif., September 1993.

[4] G. Bohannon and T. Caampued, *Debris Size Estimation from Radar Cross Section Data Using Quadratic and Non-Parametric Classifiers,* XonTech, Inc. Report No. 930301-BE2198, Van Nuys, Calif., June 1993;

[5] M.J. Matney and E. Stansbery, What are radar observations telling us about the low-Earth orbital debris environment, in *Proceeding of the Third European Conference on Space Debris,* SP-473, European Space Agency, Paris, France, October 2001.

China's Fengyun-1C satellite is different from fragments from other known events.[23] Consequently, this assumption about the relationship between shape and size needs to be reexamined, possibly leading to new ground tests to obtain representative samples and new RCS calibrations from those samples (for additional discussion on RCS calibrations, see Chapter 2).

The committee noticed a significant gap in identifying uncertainty in the more recent measurements and models, not only in those models describing the environment, but in models like BUMPER describing the risk to the environment (additional details on BUMPER can be found in Chapter 6). The committee asked for, but did not receive, uncertainty analysis, nor did it receive a comparison with model predictions and measurements, especially for those models used to predict the long-term MMOD environment. The uncertainty in these model results are not only from the statistical nature of what is being measured, where that uncertainty can be quantified and integrated into an overall risk assessment, but from assumptions that go into the models. Although the uncertainty in these assumptions cannot be assigned a probability of being correct, they can be altered within the bounds of "reasonable assumptions" to determine the sensitivity of the assumptions to the predicted risk, resulting in a range of possible risks.

Consequences of not following these principles have been identified by other NRC studies (see also, for

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[23] J.-C. Liou and N. Johnson, Characterization of the catalog Fengyun-1C fragments and their long-term effect on the LEO environment, *Advances in Space Research* 43(9):1407-1415, 2009.

example, U.S. EPA 2004[24]). These pitfalls also apply to the MMOD programs and include (1) not allowing for optimal weighting of the probabilities and consequential errors; (2) not permitting a reliable comparison of alternative decisions; (3) failing to communicate the range of control options that would be comparable with different assessments of the true state of nature; and (4) precluding the opportunity for identifying research initiatives. Examples of these pitfalls are characteristic of the CARA/COLA programs where there is a significant lack of uncertainty analysis associated with those programs (see Chapter 9).

In general, NASA MMOD programs have embraced some of the principles identified in Box 5.1. However, as both the agency and the MMOD programs mature, it becomes increasingly important to better characterize risk and uncertainty in all aspects of the MMOD problems being addressed. Other issues to be addressed include the sources of the uncertainties, how to reduce uncertainties, identifying those that cannot be significantly reduced or removed over the near term, and estimating the time and effort required to reduce significantly extant uncertainties. Of course, natural variability in the MMOD environment will prevent uncertainties from being removed entirely, no matter how sophisticated and detailed testing programs and modeling efforts become.

It is equally important that uncertainty information continue to be communicated to decision makers or program leaders because they are the ones who will determine how to handle this information within the NASA framework of mission planning and operations. While the calculation and communication of uncertainty information to decision makers, including those who plan space missions, has improved at NASA, it is also apparent that a fully integrated cataloging and assessment of MMOD-related uncertainties does not routinely occur in mission-planning and decision-making activities as noted above, this type of information is typically conveyed to management when the uncertainties are either small enough to be ignored, or large enough to be obvious so that either more data or some sort of corrective action is required. Since many of these decisions appear to be made at the program level, effective communication of uncertainty information both to the public and to the proper management levels is an issue of considerable importance that needs constant reevaluation and oversight.

> **Recommendation: NASA's meteoroid and orbital debris programs should increase their efforts to reduce the uncertainty and variability in models through acquisition of measurements (and where necessary, to do testing and analysis) for continually improving assessment of risk and characterization of uncertainty. Together with its MMOD efforts, NASA should continue to advance the agency's efforts to present information on uncertainty in risk analyses. Special attention should be given to maximizing public understanding of uncertainty analysis through peer-reviewed papers and other publications.**

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[24] Environmental Protection Agency, *An Examination of EPA Risk Assessment Principles and Practices,* EPA/100/B-04/001, Washington, D.C., March 2004.

6

Spacecraft Protection in the MMOD Environment

There are three basic approaches to protecting spacecraft against the hazards of meteoroid and orbital debris (MMOD) impacts. They are typically categorized as passive, active, or operational:[1]

- *Passive* protection approaches are applied before a spacecraft is launched. These methods typically involve spacecraft shielding, redundant system design, orbit selection to lower particulate risks, and so on.
- *Active* protection approaches are taken once a spacecraft is in orbit in order to reduce the risk to it. These activities may include, for example, the elimination of debris in the path of an orbiting spacecraft, the avoidance of collisions, or the removal of large objects to eliminate future potential debris-generating events.
- *Operational* approaches are designed to protect a spacecraft against damage from particles that are too large to actively protect against or too small to be seen and avoided. These techniques can include intelligent spacecraft attitude profiles, smart working and living arrangements (e.g., placing astronauts in areas not directly exposed to the particulate flux), and so on.

All of these approaches share a common goal—to protect a spacecraft (and its inhabitants, if any) against system loss as a result of an MMOD impact. This goal is typically translated into a design requirement that specifies a certain probability that the spacecraft will remain operational for a specified number of years in the MMOD environment. Chapter 7 focuses on ensuring the safety of a spacecraft through active means to reduce the debris that poses a hazard to the spacecraft. In addition, Chapter 3 and Chapter 4 provide a comprehensive description of the particulate environment that space systems must be able to survive. This chapter focuses on examining the probability of system failure given an MMOD impact and on the protection of spacecraft to reduce the probability of failure.

CALCULATING THE PROBABILITY OF MMOD IMPACT

NASA currently uses the BUMPER code to calculate the risk of MMOD penetration for the International Space Station (ISS), extravehicular activity (EVA) suits, and other spacecraft and also used BUMPER to calculate the probability of an MMOD impact causing critical damage for each space shuttle mission.[2] Originally developed

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[1] National Research Council, *Orbital Debris: A Technical Assessment*, National Academy Press, Washington, D.C., 1995.

[2] D. Abbott, D.R. Williams, and M.D. Bjorkman, *BUMPER-II Analysis Tool: User's Manual*, Report No. D683-29018-2, Boeing Company, Huntsville, Ala., 1993.

by Boeing under contract to NASA Marshall Space Flight Center for use on the Space Station Freedom program in 1986, the original BUMPER code was designed for use on VAX computers and is still used on workstations for space shuttle and ISS assessments. In 1991, the BUMPER code was updated to the BUMPER II code, and configuration control was established at NASA Johnson Space Center in 1994. BUMPER II (hereafter referred to simply as BUMPER) is now clearly considered the standard by which other MMOD risk assessment tools are measured—even the European and Russian space agencies have used versions of it. Two versions of BUMPER have been maintained, one for the ISS program and one for the space shuttle program. The primary differences between the two versions are in the impact damage subroutines related to different exterior materials and failure criteria.

From the perspective of a particle–spacecraft interaction that could lead to spacecraft failure, risk from a single MMOD impact may be considered to be a product of the following three terms:

- The probability of impact, or hit (PH);
- The conditional probability of penetration given that an impact has occurred (PP/PH); and
- The conditional probability that the penetration yields a loss, or kill, of spacecraft or crew given that a penetration has occurred (PK/PP).

These terms can be combined in a number of ways to determine PK for a spacecraft. For example, the first two terms (PH and PP/PH) can combine to form the probability of penetration, or PP. This is essentially what BUMPER was originally designed to do—to determine the probability of penetration of the space station—because a penetration was (conservatively) equated with a crew or station loss. It is because of this original (highly conservative) assumption that the last term—the probability of “kill” given a penetration (PK/PP)—while clearly an integral part of the total risk equation, was never designed for inclusion within BUMPER. However, the ability to quantify the PK/PP term—the vulnerability of spacecraft to loss following penetration—allows spacecraft designers to examine the entire probability of loss, thereby shifting some of the focus on increasing safety with respect to orbital debris from the external portion of the spacecraft or the ISS to the entire spacecraft design envelope, including internal equipment design, crew procedures, and other factors that contribute to potential failure modes and the overall probability of loss.

BUMPER is used as an in-line requirements compliance verification tool by the ISS and was previously used for the space shuttle, as well. It is also being used for development of the Orion Multipurpose Crew Vehicle.[3] It has been used by ISS contractors and international partners to design shielding to protect station crews and meet lifespan requirements. BUMPER has also been used to identify ways of reducing the risk posed by MMOD to within established NASA risk levels (through operations, shielding, or other means). Space shuttle mission profiles and operations were often directly affected by risk predictions based on BUMPER calculations, which resulted in a reduced risk from the MMOD environment to the vehicle.[4]

For example, BUMPER predictions were essential in determining the proper positioning of the payload bay door on STS-73 to provide MMOD protection to some otherwise lightly protected pressurized tanks within the payload bay (see Box 6.1 to view images of space shuttle damage from debris impacts). During the mission, a relatively large orbital debris particle did, in fact, impact one of the closed payload bay doors. Had it not been decided to close the door following analysis and interpretation of BUMPER data, the resulting damage to the space shuttle would have been significant. In addition, several modifications to the space shuttle were developed following analysis of BUMPER risk assessments, such as adding isolation valves to the coolant lines on the payload bay door radiators. If one of the two redundant coolant loops was penetrated by an MMOD particle, it could be isolated without affecting the operation of the remaining coolant loop.

Although BUMPER is a powerful tool, it does have some limitations. The major limitations of BUMPER are (1) that it calculates only a portion of the MMOD risk to a spacecraft (the probability of a penetration, however

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[3] Larry Price, Orion Deputy Program Manager, Lockheed Martin, “Orion Spacecraft MMOD Protection Design and Assessment,” presentation at the Workshop to Identify Gaps and Possible Directions for NASA’s Micrometeoroid and Orbital Debris Programs, March 10, 2011, National Research Council, Washington, D.C.

[4] J. Williamsen, *Review of Space Shuttle Meteoroid/Orbital Debris Critical Risk Assessment Practices*, Report No. P-3838, Institute for Defense Analyses, Alexandria, Va., November 2003.

that is defined for the particular spacecraft under consideration) and is not able to calculate the total MMOD risk (which would include the probability of spacecraft loss or kill), (2) that it provides a point estimate of MMOD risk with no assessment of its associated uncertainty, and (3) that it does not take into consideration in its risk-calculating modules and algorithms the possibility of non-spherical particle impacts. These points are discussed in more detail in the following sections.

CALCULATING THE PROBABILITY OF SPACECRAFT LOSS

As noted previously, NASA currently uses BUMPER to calculate the risk of MMOD impact that would cause mission-limiting or life-threatening damage to the International Space Station, EVA suits, or other spacecraft (and, previously, for the space shuttle).[5] This calculated value for risk, or probability of spacecraft failure, is then compared against design requirements to determine whether or not a proposed design, or a proposed design change (e.g., number of shields), will allow the spacecraft to meet its design requirements. Thus, in addition to being used to estimate the risk associated with a given design, BUMPER can also be used as a design tool, given an acceptable level of risk. However, if BUMPER is used as a design tool, the resulting design must be evaluated carefully, because BUMPER assumes that any hole is a failure, regardless of whether it is a pinhole or a 10-cm-diameter hole.

In an effort to rectify this situation (i.e., that the existing risk assessment tool then used by NASA equated all module wall penetrations to spacecraft failure or loss) for the ISS, NASA developed a separate code to specifically calculate the probability of a spacecraft loss given a penetration of the crewed habitation modules. This computer program is known as the Manned Spacecraft and Crew Survivability (MSCSurv) code. Unlike BUMPER, MSCSurv has the ability to compute the uncertainty associated with its output as well as the potential for expansion for use with NASA robotic spacecraft.[6,7]

Once a penetration occurs, MSCSurv initiates its process of quantifying how the possible hazards associated with the penetration contribute to the probability of crew or station loss. Currently seven general hazards or “loss modes” that are considered a catastrophic loss (or kill) are analyzed by MSCSurv as a result of debris particles penetrating crewed modules:

- External equipment loss,
- Critical cracking,
- Internal systemic loss,
- Internal payload loss,
- Crew hypoxia during escape or crew member rescue,
- Fatal injury to crew, and
- Thrust-induced angular velocity departure loss.

In addition, MSCSurv considers three other hazards, two of which could lead to a late loss of the station:

- Non-fatal injury to crew,
- Late loss of station control, and
- Critical module depressurization.

Developed in recognition of BUMPER’s structure, input, outputs, and limitations, the MSCSurv program has never been integrated directly with BUMPER into a single program. This level of integration is possible and may offer improvements in removing the duplication in input files, geometry files, and others. A new code integrating

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[5] Abbott et al., *BUMPER-II Analysis Tool: User’s Manual*, 1993.

[6] J. Williamsen, *Vulnerability of Manned Spacecraft to Crew Loss from Orbital Debris Penetration,* NASA TM-108452, NASA, Huntsville, Ala., April 1994.

[7] H. Evans, K. Blacklock, and J. Williamsen, *Manned Spacecraft & Crew Survivability (MSCSurv) Version 4.0 User’s Guide,* Report No. 651-001-97-006, Sverdrup Technology, Inc., Huntsville, Ala., September 1997.

BOX 6.1
Meteoroid and Orbital Debris Strikes on the Space Shuttle

In orbit for up to 3 weeks at a time, the space shuttles were not immune to the dangers posed by meteoroids and orbital debris. See Figures 6.1.1 through 6.1.4. NASA checked critical space shuttle surfaces, such as windows, after every flight, on average replacing two shuttle windows per mission as a result of MMOD damage.

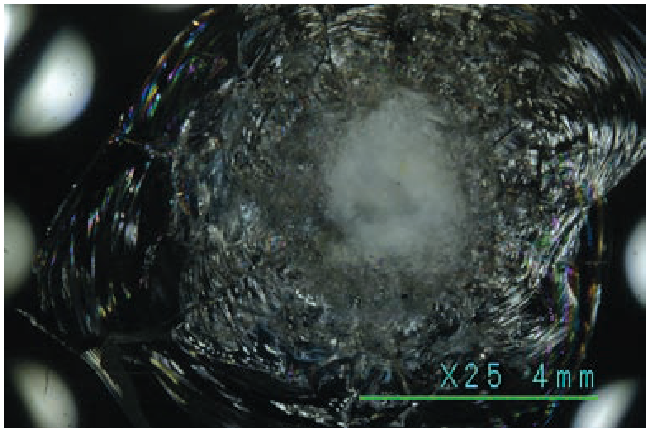

FIGURE 6.1.1 Digital microscope image of impact to window #6 from STS-126. SOURCE: Courtesy of NASA, from J. Herrin, J. Hyde, E. Christiansen, and D. Lear, STS-126 shuttle Endeavour window impact damage, *Orbital Debris Quarterly News* 13(2):4, April 2009.

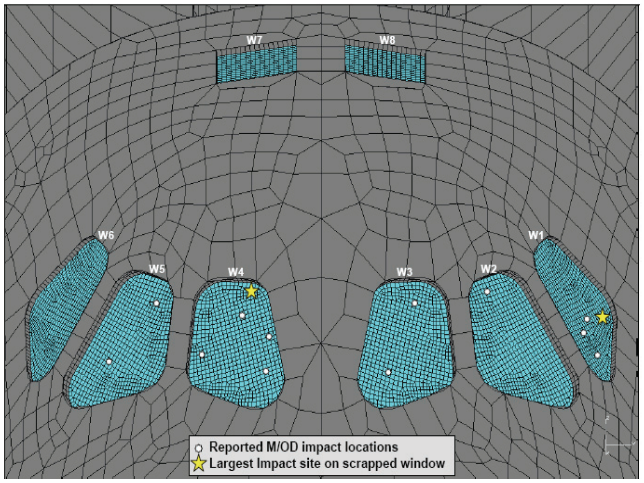

FIGURE 6.1.2 Crew module window impact map from space shuttle *Discovery*'s STS-114 mission in July 2005. There were 14 MMOD impacts on the crew module windows, and a total of 41 MMOD impacts sites on *Discovery* from its 13-day mission. The largest impact feature was a 6.6 mm by 5.8 mm crater on window #4. SOURCE: Courtesy of NASA, from J. Hyde, R. Bernhard, and E. Christiansen, STS-114 micrometeoroid/orbital debris (MMOD) post-flight assessment, *Orbital Debris Quarterly News* 10(3):2, July 2006.

BOX 6.1 (Continued)

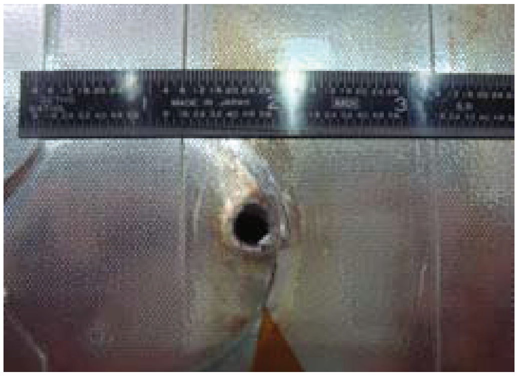

FIGURE 6.1.3 MMOD impact of the space shuttle *Endeavour* from the August 2007 STS-118 mission. The puncture in *Endeavour's* left-side aft-most radiator panel measured 8.1 mm by 6.4 mm, but the exit hole through the radiator's backside facesheet measured 14 mm by 14 mm. *Endeavour* also had two impacts on its thermal control system blanket on this mission. SOURCE: Courtesy of NASA, from D. Lear, J. Hyde, E. Christiansen, J. Herrin, and F. Lyons, STS-118 radiator impact damage, *Orbital Debris Quarterly News* 12(1):3, January 2008.

FIGURE 6.1.4 MMOD impact damage to window #6 on space shuttle *Endeavour* during STS-126 mission in November 2008. The impact damage measures 12.4 mm by 10.3 mm (measured parallel to the glass surface), with a depth of 0.62 mm. According to NASA's Orbital Debris Program Office, this is the largest shuttle window impact ever observed. SOURCE: Courtesy of NASA, from J. Herrin, J. Hyde, E. Christiansen, and D. Lear, STS-126 shuttle Endeavour window impact damage, *Orbital Debris Quarterly News* 13(2):4, April 2009.

both BUMPER and MSCSurv features would allow a more comprehensive evaluation of risk and of the effect of input uncertainties on output risk evaluations.

> **Finding: The BUMPER program was not designed to fully address the probability of spacecraft failure following penetration by a meteoroid(s) or pieces of orbital debris.**
>
> **Recommendation: NASA's own MSCSurv code might offer insights for development of an expanded, improved MMOD risk analysis code that fully addresses the risk to a valuable spacecraft following an MMOD impact and, as such, should be coupled with results from BUMPER for use as needed.**

As discussed elsewhere in this report, hypervelocity impacts are known to produce significant amounts of plasma, and plasma poses a real and present danger to satellite operations. As codes like MSCSurv and Bumper are updated in the future and made applicable to a broader class of spacecraft (and not just large, habitable vehicles like the space shuttle, Orion, or the ISS), the effects of molten or vaporous material and impact-induced plasma should be included in the updated modeling efforts.

CONSIDERATIONS REGARDING UNCERTAINTY IN BUMPER

The uncertainties in BUMPER predictions of MMOD risk come primarily from three areas: damage prediction/ballistic limit equations, environment models, and criteria for defining failure. To attempt to quantify the overall uncertainty bounds on BUMPER MMOD risk predictions, the uncertainty in each of these three areas must be identified. At present, BUMPER provides point estimate predictions of MMOD risk for a given set of input mission parameters but does not provide uncertainty bounds or confidence intervals for its predictions. This makes it difficult to fold the results of BUMPER runs into a formal, end-to-end statistics-based probabilistic risk assessment. With so many uncertainties present in the models used within BUMPER, providing uncertainty bounds with BUMPER results is essential to properly evaluating and understanding this component of the overall MMOD environment risk.

The space shuttle and ISS versions of BUMPER use a variety of equations to predict damage to system components in terms of an impacting particle's density, velocity, and angle of impact. Some equations are developed by simply drawing a curve through fail/no-fail test data (the so-called ballistic limit equations, or BLEs), while others are developed by performing statistical curve-fits to empirical data (the damage predictor equations, or DPEs). Once a critical damage level is identified for a particular spacecraft component, an appropriate DPE or BLE is manipulated, if necessary, into a form that yields the critical diameter of a particle whose impact would result in the critical damage level.

Damage Predictor Equations

The DPEs are curve-fits to empirical data; that is, they are the results of statistical regression analyses of available test data. As such, uncertainty bounds and/or confidence intervals can be obtained at the time that the regression analyses are being performed to form the DPEs.

Ballistic Limit Equations

Unlike the DPEs, the BLEs are not statistically based. They are not curve-fits, but rather are simply lines of demarcation between regions of penetration and non-penetration in regions where test data exist. In regions where test data does not exist, lines are drawn based on assumed forms and assumed exponents of various terms. As a result, and also unlike for the DPEs, it is simply not possible to obtain uncertainty bounds and/or confidence intervals as part of the current procedure that is used to derive the BLEs. Alternative, innovative approaches must be developed to either (1) obtain uncertainty information from existing BLEs and the data on which they are based or (2) re-derive the BLEs using a statistics-based approach so that uncertainty information is forthcoming out of the analyses along with the equations themselves. Both of these options, as well as suggested approaches for their implementation, are discussed in more detail in Schonberg et al. (2005).[8]

Uncertainty Modeling Beyond the Testable Regime

The approaches discussed previously can only be used to provide uncertainty bounds and/or confidence intervals for BLEs in the tested regime (typically for impact velocities between 3 and 7 km/s). Since the average impact velocity of orbital debris is expected to be close to10 km/s and the average impact velocity for meteoroids is predicted to be close to 20 km/s (when corrected to a limiting mass), the majority of MMOD debris impacts are expected to occur at speeds in excess of 7 km/s, with a small fraction having velocities in excess of 60 km/s. These impact velocities are beyond the upper-limit capability of nearly all light gas guns. While it is possible to reach higher impact velocities using alternative launching technologies, none of these alternative technologies has the repeatability and consistency of the light gas gun. Therefore, another approach is needed to determine the uncertainty characteristics of the BLEs in BUMPER at speeds beyond 7 km/s or the ability to launch massive enough particles at speeds above 7 km/s.

Current Efforts to Model Uncertainty

NASA has recently performed a series of studies aimed at establishing uncertainty bounds for BUMPER calculations of MMOD risk for the space shuttle and Orion program offices; plans are currently in place to calculate ISS MMOD risk uncertainties using similar procedures. These uncertainty bounds were estimated using a Monte Carlo method wherein the BUMPER code was executed multiple times, while varying the program inputs for the environment, the BLEs, the failure criteria, and the operational parameters.[9,10] However, the uncertainty distributions that were input into BUMPER for these calculations were "heuristic" at best; they were estimates provided by subject matter experts, assumed without much supporting data. This process needs increased rigor so that the uncertainty results are also more rigorous.

> **Finding: It is not possible to obtain uncertainty bounds and/or confidence intervals as part of the current procedures being used to derive damage predictor equations in BUMPER.**
>
> **Recommendation: Considering the critical need to develop overall uncertainty bounds for predictions of MMOD impacts (which in turn could be used in a probabilistic risk assessment), NASA should refine its damage prediction models so that they include uncertainty bounds and/or confidence intervals.**

Debris Shape—Considerations and Effects

It was recognized early in the 1970s that projectile shape would add a component to the failure mechanisms experienced during the hypervelocity impact of a double-sheet structure, also known as the Whipple bumper shield.[11] The impact of arbitrarily shaped projectiles (discs, rods) did considerably more damage to the back wall of a Whipple shield configuration when compared with impact damage caused by spherical projectiles of the same mass.[12] For the smaller projectiles, on the order of the thickness of a typical spacecraft wall (i.e., several millime-

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[8] W.P. Schonberg, H.J. Evans, J.E. Williamsen, R.L. Boyer, and G.S. Nakayama, Uncertainty considerations for ballistic limit equations for aerospace structural systems, *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, Paper No. IMECE-2005-79709, Orlando, Fla., American Society of Mechanical Engineers, New York, N.Y., November 2005.

[9] E. Christiansen, J. Hyde, T. Prior, and D. Ochoa, "BUMPER-II Meteoroid/Orbital Debris Risk Sensitivity Study," presented to NASA Code Q, Washington, D.C., 2004.

[10] NASA, *Lightweight Installable Micrometeoroid and Orbital Debris (MMOD) Shield Concepts for International Space Station (ISS) Modules,* Report No. NESC-RP-09-00593m, NASA Engineering and Safety Center, Washington, D.C., 2011.

[11] R.H. Morrisson, *Investigation of Projectile Shape Effects in Hypervelocity Impact of a Double-Sheet Structure,* NASA TN D-6944, NASA, Washington, D.C., 1972.

[12] See A.J. Piekutowski, Debris clouds generated by hypervelocity impact of cylindrical projectiles with thin aluminum plates, *International Journal of Impact Engineering* 5:509-518, 1987; E.L. Christiansen and J.H. Kerr, Projectile shape effects on shielding performance at 7 km/s

ters), the fragments produced from hypervelocity impact tests were found to have fairly small length-to-diameter (L/D) ratios. As projectiles got larger, on the order of several centimeters, they began to have a wider range of L/D ratios. In such cases, the effects of shape did indeed become more pronounced and would provide a wider range of penetration results for a given characteristic size depending on the orientation at impact. However, these larger projectiles are much less populous in the near-Earth environment and exceed the ballistic limit of most spacecraft shields, regardless of their orientation.

Orbital debris risk assessments performed by NASA through BUMPER use ballistic limit equations that have been developed using high-speed-impact test data and results from numerical simulations that have used spherical projectiles. However, it has become increasingly evident that consideration of particle shape and impact orientation could produce a pronounced effect in reducing predicted risk of failure from MMOD impacts.[13,14] Not including the effects of orbital debris shape (and attendant variations in impact orientations) in debris models and risk assessment tools appears to bias the risk results toward a conservative, overprediction of risk.

It is also important to note that computer modeling of shape and orientation effects as well as computerized risk evaluations (using Monte Carlo approaches) have become powerful enough to allow (or even require) the consideration of shape effects for large, long-lived space vehicles such as the ISS. For example, the Department of Defense has developed FATEPEN, a computer model used for just such a purpose in aircraft, vehicle, and ship vulnerability assessment.[15] When developing and providing orbital debris models and damage prediction tools that include the effects of shape and orientations, NASA should leverage this development for potential application in its suite of MMOD effects analysis tools and models.

Since the orbital debris environment is presented in terms of characteristic length and the NASA Standard Breakup Model (SBM) relates characteristic length to shape, it appears that the NASA SBM would be an appropriate first-order model to include as an adjunct to the ORDEM2010 model release as a means of connecting the parameter used to define the man-made particulate environment to a key parameter used in high-speed impact testing of candidate spacecraft design configurations. In some regard, shape has always been included by NASA in characterizing the orbital debris environment, beginning with the sensors used to measure the environment, then extending to the mathematical modeling performed to reduce those measurements to some sort of "size," and then to the presentation of this information in terms of a particle flux versus a particle characteristic length to define the debris environment. However, when the Hypervelocity Impact Technology Facility performs high-speed impact testing to develop a BLE for a particular spacecraft component, that "characteristic length" is taken to mean "diameter," and those tests are subsequently conducted using spherical projectiles. Williamsen et al. (2011) provide evidence that a sphere may not be the most benign shape on an equivalent characteristic length basis;[16] spheres can penetrate a spacecraft wall, whereas other equal characteristic length objects may not.

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and 11 km/s, *International Journal of Impact Engineering* 20:165-172, 1997; B.G. Cour-Palais, The shape effect of non-spherical projectiles in hypervelocity impact, *International Journal of Impact Engineering* 26:129-144, 2001; A.J. Piekutowski, Debris clouds produced by the hypervelocity impact of nonspherical projectiles, *International Journal of Impact Engineering* 26:613-624, 2001; K. Hu and W.P. Schonberg, Ballistic limit curves for non-spherical projectiles impacting dual-wall systems, *International Journal of Impact Engineering* 29:345-356, 2003; F. Schäfer, S. Hiermaier, and E. Schneider, Ballistic limit equation for the normal impact of unyawed ellipsoid-shaped projectiles on aluminium whipple shields, in *Proceedings of the 54th International Astronautical Congress (IAC): Space Debris and Space Traffic Management*, (J. Bendisch, ed.), September 29-October 3, 2003, Bremen, Germany, Paper No. IAA-03-5.3.06, International Academy of Astronautics, Paris, France, 2003; W.P. Schonberg and J.E. Williamsen, RCS-based ballistic limit curves for non-spherical projectiles impacting dual-wall spacecraft systems, *International Journal of Impact Engineering* 33:763-770, 2006; J.E. Williamsen and S.W. Evans, Predicting orbital debris shape and orientation effects on spacecraft shield ballistic limits based on characteristic length, *International Journal of Impact Engineering* 33:862-871, 2006; and J.E. Williamsen, W.P. Schonberg, H. Evans, and S. Evans, A comparison of NASA, DOD, and hydrocode spherical and non-spherical ballistic limit predictions for dual-wall targets and their effect on spacecraft risk, *International Journal of Impact Engineering* 35:1870-1877, 2008.

[13] J.E. Williamsen, W.P. Schonberg, and A.B. Jenkin, On the effect of considering more realistic particle shape and mass parameters in MMOD risk assessments, *Advances in Space in Research* 47:1006-1019, 2011.

[14] J. Williamsen, *Review of Space Shuttle Meteoroid/Orbital Debris Critical Risk Assessment Practices,* Report No. P-3838, Institute for Defense Analyses, Alexandria, Va., November 2003.

[15] J. Yatteau, R. Zernow, G. Recht, and K. Edquist, *FATEPEN (Version 3.0.0) Terminal Ballistic Penetration Model: Volume I—Analyst's Manual,* Applied Research Associates, Naval Surface Weapons Center, Dahlgren, Va., 2005.

[16] J.E. Williamsen, W.P. Schonberg, and A.B. Jenkin, On the effect of considering more realistic particle shape and mass parameters in

As NASA's understanding of the orbital debris environment has improved, so also has its use of shape in the characterization of that environment. Initially, shape was handled with a decreasing mass density with increasing spherical particle diameter. In theory, it was just a matter of defining an "effective" mass density that would give the correct rate of penetration. However, during that time, hypervelocity tests were conducted that showed that shape had a greater effect on damage than the reduced mass density function predicted. Therefore, it appears that relative size variations and distributions must be considered at the same time as shapes and orientations in order to reach conclusions regarding the effects of particle shape on impact damage (e.g., the effect of a cylinder hitting "end on" must be balanced with the likelihood of such an orientation). This can be achieved through developing ballistic limit curves for particular shapes and orientations taken together using such programs as FATEPEN, and then feeding them into BUMPER, which considers their size and velocity, and determines risk of penetration.

The effects of the shapes of non-spherical orbital debris particles would be seen more often in larger, longer-lived satellites (such as the ISS) than in smaller, shorter-lived satellites because larger, longer-lived satellites are more likely to be impacted by larger particles over time than are smaller, shorter-lived satellites. Whether or not shape effects are important might thus depend on whether the problem is approached by a compact satellite breakup expert or robotic spacecraft mission failure analyst as opposed to someone who is thinking about the operational issues related to habitable spacecraft being impacted by a piece of debris.

In the compact satellite arena, the main driver in a risk assessment calculation is likely the debris that would cause a failure in a robotic spacecraft. In this case, penetration is fairly important (e.g., penetrating an exposed umbilical, degrading a solar array, and so on), as is when, or if, the object is large enough to create more debris by breaking up. Compact, robotic satellites are less likely to be affected by shape effect considerations because once a particle penetrates into such a structure, the effect becomes more a matter of momentum and energy transfer to the structure rather than a matter of particle shape.

However, in the habitable module and rocket body arena, particle shape may indeed become more important, because a large hole in a crewed spacecraft does create a problem completely different from that caused by a small pinhole. The interior effects of a penetration for large spacecraft (such as the ISS, where hypoxia may drive crew loss evaluations) are probably more dependent on the size and shape of the hole, which in turn are themselves dependent on the shape and impact orientation of the original particle.

According to NASA's Standard Breakup Model,[17] the larger particles are more likely to have higher length-to-diameter ratios, but to be much less massive than a sphere of the same characteristic length. According to this same model, particles smaller than 1 mm are more likely to be chunkier and more cube-shaped, more closely approximating a sphere. However, until recently, very little research has been performed on the effects of such particles on assessed spacecraft risk. One of the reasons might be that, for small satellites, the likelihood of impact and assessed risk values are sufficiently small using even more conservative spherical shape effects. If a first-order assessment using a spherical debris shape assumption renders an assessed risk that is sufficiently small, no further assessments using more complex particles should be necessary. However, for larger, longer-lived spacecraft such as the ISS, a more rigorous analysis considering non-spherical shapes may be more appropriate, and a debris model that provides guidance for actual debris shapes is needed.

A preliminary review of the upcoming ORDEM2010 release indicates that NASA is continuing the practice of suggesting that the characteristic length of an orbital debris particle can be equated to the diameter of a spherical projectile provided that the mass density of the spherical particle decreases with increasing size. The difficulty with that approach is that when one attempts to perform high-speed-impact tests to characterize the damage that would be sustained by a spacecraft when struck by the larger particles, one is constrained by the availability and choices of naturally occurring materials from which the projectiles could be made—one would need to use either hollow spheres, solid spheres filled with voids, or an unrealistic material. In the first two cases, of course, the

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MMOD risk assessments, *Advances in Space in Research* 47:1006-1019, 2011.

[17] R.C. Reynolds, A. Bade, P. Eichler, A.A. Jackson, P.H. Krisko, M.J. Matney, D.J. Kessler, and P.D. Anz-Meador, *NASA Standard Breakup Model, 1998 Revision,* Report No. LMSMMSS-32532, Lockheed Martin Space and Mission Systems and Services, Houston, Tex., 1998.

penetration mechanics would be completely different from those for the original debris particle. It would appear, therefore, that given the choice of either changing the density of spheres or using an "SBM flake" with a changing form to capture the effects of the shape of orbital debris particles, from a penetration mechanics standpoint the SBM flake is far superior.

Finding: Using aluminum spheres to develop ballistic limit equations for risk assessments for spacecraft may not accurately portray the range of damage likely from impact with an orbital debris particle of any given characteristic size and thus may result in a non-optimum design of the spacecraft's MMOD protection systems.

Recommendation: A priority in the next release of the Orbital Debris Environment Model and Standard Breakup Model should be the inclusion of shape characteristics in the particle distributions to more accurately portray the range of potential damage from an impact with orbital debris.

7

Mitigation of Orbital Debris

President Reagan's 1988 National Space Policy directed that "all space sectors will seek to minimize the creation of space debris . . . consistent with mission requirements and cost effectiveness." At that time, the NASA orbital debris program had already established procedures to minimize the possibility of growth in the debris population from future explosions of the U.S. Delta 2nd stage, and had approached the European Space Agency (ESA) concerning a similar problem with ESA's Ariane upper stage. These were the events that began NASA's involvement in establishing standards for mitigation of orbital debris on an international basis.

Political, legal, technical, and economic considerations had to contribute to any standards that were established. The political and legal issues are discussed in Chapter 11. The economic issues were considered by consulting with the manufacturers and operators of space hardware. For example, most upper-stage rockets either have the ability to deplete the excess fuel remaining after delivering their payload, or could have that ability with a simple modification. Consequently, implementation of the mitigation standard for a spacecraft and upper stages to deplete their on-board stored energy after mission operations began in the early 1980s, well before there were any written requirements. This single mitigation action greatly reduced the risk of accidental explosions for those who exercised it and lowered the growth rate of cataloged fragments resulting from rocket body explosions from 150 fragments per year between 1964 and 1984 to only 50 fragments per year for the next 20 years (see Figure 1.2).

Other mitigation standards, such as minimizing any debris intentionally released, also had minimal impact on mission costs and were quickly accepted by the community. However, by the early 1990s it was becoming increasingly obvious that for as long as any object was in orbit it would always be subject to the external energy source of kinetic energy. The kinetic energy involved in collisions between cataloged objects is much greater than most remaining internal energy and is therefore capable of producing even more fragments than explosions. Consequently, it was concluded that the increasing accumulation of orbital mass in the form of intact spacecraft and upper stages would inevitably lead to collisions between these objects and become the dominant source of future debris.[1] While there was uncertainty in when collisions would become the dominant source of debris, there was concern that at some point in the near future the rate of growth in low Earth orbit (LEO) would become irreversible. This led to a mitigation standard for upper stages and payloads at the end of their mission to either maneuver

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[1] Interagency Group (Space) for the National Security Council, *Report on Orbital Debris*, Washington D.C., February 1989; D.J. Kessler, Orbital debris environment for spacecraft in low Earth orbit, *Journal of Spacecraft and Rockets* 28(3):347-251, 1991; J.P. Loftus, Jr., D.J. Kessler, and P.D. Anz-Meador, Management of the orbital debris environment, *Acta Astronautica* 26(7):477-486, 1992; D.J. Kessler and J.P. Loftus, Jr., Orbital debris as an energy management problem, *Advances in Space Research* 16(11):139-144, 1995.

to one of a set of defined disposal regions or maneuver to an orbit where atmospheric drag would remove the object within 25 years.

The rationale for 25 years rather than any other time period was that it was an acceptable compromise between the amount of fuel required to maneuver to a lower orbit, and the effectiveness of such a maneuver to the long-term environment, as a result of predictions by various orbital debris models. Models such as NASA's LEGEND and the earlier EVOLVE have consistently predicted that there is only a small difference in the long-term environment between an object being removed immediately and 25 years later. Before ESA accepted the 25-year rule, ESA considered everything from zero years to 100 years for a post-mission lifetime, using the ESA MASTER'99 model. ESA concluded that "a 25-year post-mission lifetime is the shortest possible before propellant requirements start to become disproportionately high."[2]

Finding: NASA's current orbital debris programs are recognized both nationally and internationally as leaders in providing support for defining the environment and related impact hazards associated with orbital debris, and mitigation techniques to effectively minimize the hazards associated with the current and future orbital debris environment.

Finding: Most relevant federal agencies accept all or some of the components of NASA's orbital debris mitigation and prevention guidelines.

There are two problems with the current post-mission disposal standards: (1) As described in Chapter 11, "Issues External to NASA," not all of the spacecraft community are required to follow NASA's standards, with at least one U.S. agency not even encouraging compliance with the 25-year rule.[3] (2) Current model predictions conclude that even 90 percent compliance is insufficient to prevent future debris growth in LEO. These same models predicted the collision rates that are observed from the past four collisions between cataloged objects, as well as the amount of debris generated as a consequences of China's anti-satellite test (Box 1.2 in Chapter 1) and the accidental Iridium–Cosmos collision (Box 9.1 in Chapter 9), providing additional evidence that the models are correct, and that mitigation alone is not sufficient. The possibility that current mitigation standards may not be adequate requires either more aggressive mitigation or the introduction of removal operations; however, the agency is not prepared for either.

The only study to determine what actions would result in a stable orbital debris environment concluded that the retrieval of pre-selected objects could do so, and would be significantly helped by compliance with the 25-year rule.[4] A study by both NASA and ESA has identified some alternative techniques to remove objects.[5] However, the largest activity was the "International Conference on Orbital Debris Removal" in Chantilly, Virginia, on December 8-10, 2009, sponsored by NASA and the Defense Advanced Research Projects Agency (DARPA). The conference identified many possibilities, but all required further technology development, most raised legal issues, and some introduced policy conflicts. A few might be more accurately described as enhanced or active mitigation. A report to DARPA after the conference included the observation that "any future debris removal strategy must be tested to ensure that it will work in the operating environment."[6] None of the removal or "enhanced mitigation" concepts have been fully tested or tried in the operating environment.

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[2] R. Walker, C. Martin, H. Stokes, J. Wilkinson, H. Sdunnus, S. Hauptmann, P.Beltrami, and H. Klinkrad, Executive summary, in *Update of the ESA Space Debris Mitigation Handbook,* Ref. QINETIQ/KI/SPACE/CR021539, European Space Agency, Paris, France, July 2002, available at www.esa.int/gsp/completed/execsum00_N06.pdf.

[3] National Research Council, *Summary of the Workshop to Identify Gaps and Possible Directions for NASA's Micrometeoroid and Orbital Debris Programs*, The National Academies Press, Washington, D.C., 2011.

[4] J.-C. Liou, N.L. Johnson, and N.M. Hill, Controlling the growth of future LEO debris populations with active debris removal, *Acta Astronautica* 66(5-6):648-653, 2010.

[5] H. Klinkrad and N.L. Johnson, "Sustainable Use of Space through Orbital Debris Control," Paper AAS 10-016 presented at the 33rd Annual AAS Guidance and Control Conference, Breckenridge, Colo., February 6-10, 2010; also in *Advances in the Astronautical Sciences* 137:63-74, 2010.

[6] D. Baiocchi and W. Welser IV, *Confronting Space Debris, Strategies and Warnings from Comparable Examples including Deepwater Horizon,* prepared for DARPA by RAND Corporation, Defense Advanced Research Projects Agency, Arlington, Va., 2010.

FIGURE 7.1 LDEF was returned to Earth using the space shuttle. The space shuttle also returned the Satellites Palapa and Weststar; however, these satellites were "cooperative" in that they were stable and designed to be handled by the space shuttle. Returning a possibly spinning satellite that was not designed to be handled is a more difficult problem, even more so without the capabilities of a crewed space shuttle. SOURCE: Courtesy of NASA-JSC.

Objects have been removed from orbit, such as the LDEF satellite shown in Figure 7.1, but these were planned and designed for easy removal using the space shuttle. Various concepts for removing debris are discussed in DARPA's recently released "Catcher's Mitt" Final Report,[7] and include the use of nets and harpoons to capture large objects, and tethers, drag augmentation devices, and solar sails to remove the objects. Other potential removal solutions that have flown in orbit or been tested on the ground are electrodynamic and momentum tethers; drag augmentation devices; solar sails; ground-based and space-based lasers; and soft-catch collection media. Many show some promise; however, necessary safeguards must also be addressed and tested to ensure that any operation system does not contribute to the production of orbital debris through unintentional consequences.

Finding: Enhanced mitigation standards or removal of orbital debris are likely to be necessary to limit the growth in the orbital debris population. Although NASA's orbital debris programs have identified the need for orbital debris removal, the necessary economic, technology, testing, political, or legal considerations have not been fully examined, nor has analysis been done to determine when such technology will be required.

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[7] W. Pulliam, *Catcher's Mitt Final Report,* Tactical Technology Office, Defense Advanced Research Projects Agency, Arlington, Va.

8

Hazards Posed by Reentry of Orbital Debris

Some orbital debris may eventually reenter the atmosphere. This usually occurs through a gradual process of orbital energy removal associated with air drag. The timescale for debris orbital decay depends on orbital altitude and the ratio of surface area to mass of the debris; the larger the area-to-mass ratio, the faster the debris decays. At altitudes of 600 km, typical timescales for the smallest tracked orbital debris (10 cm) to decay is 12 to 18 months, whereas at 1,000 km the lifetime may be centuries. Note that reentry is controlled strongly by changes in air density in the upper atmosphere, which is modulated by solar activity. At times of high solar activity, the upper atmosphere is heated and expands; this tends to hasten the rate of debris orbit decay.

The vast majority of reentering debris is too small to survive reentry; it is entirely consumed in the upper atmosphere via melting and vaporization. Larger debris, especially debris made of high-melting-point materials such as titanium or stainless steel, however, may survive partially or in full to reach the ground (see Boxes 8.1 and 8.2).

Removing derelict space objects to reduce orbital debris hazards is merely a transferring of risk from space to the ground, which must also be managed. NASA Technical Standard (STD) 8719.14 dictates that the risk to people on the ground worldwide from the reentry of a piece of space hardware must not pose a hazard greater than 1 in 10,000.[1] Adherence to the probabilistic casualty metric can be determined by using one of two NASA applications: the Debris Assessment Software (DAS) and the Object Reentry Survival Analysis Tool (ORSAT).

The Debris Assessment Software (DAS) is a tool developed to provide NASA programs a simple step-by-step menu-driven application for orbital debris assessments (ODAs) that are compliant with STD 8719.14. If ODAs show non-compliance, DAS provides a means to examine debris mitigation options to meet compliance standards. DAS, however, should not be confused with ORDEM, which provides the opportunity to analyze the more technical aspects of the debris environment. Evaluation of hardware reliability, shield design, and other parameters will require engineering tools such as ORDEM and BUMPER. It is important to note that STD 8719.14 contains the actual mission requirements, while DAS is only a software tool that assists in determining compliance.[2]

DAS produces a first-order assessment of human casualty risks associated with uncontrolled space object reentries that, by design, yields a slightly conservative result. If a program or project meets reentry risk requirements using DAS, no more calculations are required. However, if a program or project does not meet requirements for reentry risk using DAS, then ORSAT will need to be exercised.

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[1] NASA, *Process for Limiting Orbital Debris,* NASA-STD 8719.14 (Change 4), Washington, D.C., September 2009.

[2] NASA, *Debris Assessment Software (DAS) User's Guide,* JSC 64047, NASA Johnson Space Flight Center, Houston, Tex., November 2007.

BOX 8.1
Cosmos (Kosmos) 954

Cosmos 954 was a Soviet nuclear-powered Radar Ocean Reconnaissance Satellite (RORSAT) that launched from the Baikonur cosmodrome on September 18, 1977.[1] Only 4 months later on January 24, 1978, Cosmos 954 crashed into Canada's Northwest Territories, scattering large amounts of radioactive material across 124,000 km^2, from Great Slave Lake into northern Saskatchewan and Alberta.[2] Only one in a series of satellites, Cosmos 954 and the other RORSATs operated at very low altitudes to conduct their surveillance of ocean traffic with space-based radar, which required them to expend a significant amount of fuel and energy to keep their station. To produce the energy necessary for this type of operation, the RORSATs used a nuclear power source. Typically, just before the fuel is spent in a RORSAT, its operators send the satellite into a higher "graveyard" orbit between 800 km and 1,000 km. Unfortunately, Cosmos 954's propulsion system failed for reasons unknown, causing it to reenter Earth's atmosphere before it could be sent to the graveyard orbit. In the end, the joint U.S.–Canadian clean-up operation recovered only approximately 0.1 percent of Cosmos 954's power source.[3] This event also marked the first time that the adjudicative process built into the UN Convention on International Liability for Damage Caused by Space Objects[4] was put to the test. In 1981, the Soviet Union (USSR) and Canada settled the Canadian's claim of reimbursement, and the USSR paid the Canadians $3,000,000.[5]

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[1] See http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1977-090A.
[2] See http://www.hc-sc.gc.ca/hc-ps/ed-ud/fedplan/cosmos_954-eng.php.
[3] See http://www.hc-sc.gc.ca/hc-ps/ed-ud/fedplan/cosmos_954-eng.php.
[4] See http://www.oosa.unvienna.org/oosa/SpaceLaw/liability.html.
[5] See http://www.jaxa.jp/library/space_law/chapter_3/3-2-2-1_e.html.

ORSAT is a semi-empirical model that determines survivability of reentering hardware (debris, payloads, and rocket bodies).[3] This tool can be used for both controlled and uncontrolled reentry. The predicted amount of material surviving to the ground is determined, the resulting impact hazard is calculated, and this hazard is compared to the impact hazard threshold.

The ORSAT model is a suite of tools that perform trajectory, atmospheric, aerodynamic, thermodynamic, and thermal/ablation physics calculations. These algorithms together determine if the space object, or any of its remnants, will survive reentry. Different object types and shapes can also be modeled with ORSAT. Both tumbling and spinning objects can be simulated in the trajectory model. Physical parameters that change during the course of reentry, such as coefficient of drag and stagnation heating rates, are determined by modifying a well-validated circular object for varying shape effects. If the absorbed heat exceeds the heat of ablation for the material, then the object is assumed to have disintegrated. (See Figure 8.1 for an example.)

Temperature-varying properties such as thermal conductivity, specific heat, and surface emissivity are included in ORSAT for nearly 100 materials. If the model predicts that an object is within a small margin of the threshold for total destruction, extra calculations are performed to consider oxidation efficiency, initial temperature, surface emissivity, number of hardware layers, dimensions, and breakup altitude. This additional examination will provide a more accurate determination of object survival to the ground. The total debris casualty ground coverage is calculated by combining ground footprint and object survival estimates. The impact casualty risk is determined by combining the predicted mass of the surviving object mass with a worldwide population distribution model. This value is then used to discern whether the space object reentry scenario is compliant with STD 8719.14.

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[3] R.N. Smith, J. Dobarco-Otero, K.J. Bledsoe, and R.M. DeLaune, *User's Guide for Object Reentry Survival Analysis Tool (ORSAT)—Version 6.0,* JSC-62861, NASA Johnson Space Flight Center, Houston, Tex., January 2006.

BOX 8.2
Validation of Reentry Hazard Models

The NASA Orbital Debris Program Office (ODPO) has supported other NASA programs, the Department of Defense, the Federal Aviation Administration, the National Oceanic and Atmospheric Administration, the Department of Justice, and foreign entities in predicting the hazard posed by reentry of space hardware. It takes full advantage of actual reentry events to validate its reentry models to the maximum extent possible. Usually, these reentry events start with a private citizen finding an unusual object on the ground. The committee was presented with examples of 10 such objects, found in locations all over the world. The NASA website[1] as well as a publication by the Aerospace Corporation includes examples of recovered reentered space hardware.[2] The following recent example of a recovery analysis illustrates that it takes a certain amount of determination to add data on a piece of reentered debris into the NASA database.

In March, 2011, Robert Dunn was hiking in Moffat County, near the NW corner of Colorado. He heard a high-pitched sound that he could not identify, but it caught his attention since he was in a fairly isolated area. A short time later, he noticed a 30" diameter object on the ground within a crater about a foot deep. The object was warm when he touched it, even though he was in an area with snow on the ground.[3] Feeling that the object had to have come from space, he contacted NORAD to get more information. NORAD suggested that he contact his local sheriff. Mr. Dunn ended up contacting both the local sheriff and NASA's retired scientist, Don Kessler, both of whom pointed Mr. Dunn to NASA's ODPO. The ODPO was able to identify the object as a spherical titanium tank originating from a Russian upper-stage rocket launched in January 2011.[4] The Russian writing on the object, and a visit from a Ukrainian news crew from where the tank was designed, pretty much confirmed the origin. A follow-up search found another, smaller sphere 34 miles to the North-East.

FIGURE 8.2.1 Robert Dunn and the Russian space debris. SOURCE: Courtesy of Elizabeth Campbell.

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[1] See NASA Orbital Debris Program Office, "Orbital Debris Recovered Objects," available at http://www.orbitaldebris.jsc.nasa.gov./reentry/recovered.html.

[2] W. Ailor, W. Hallman G. Steckel, and M. Weaver, Analysis of reentered debris and implications for survivability, pp. 539-544 in *Proceeding of the Fourth European Conference on Space Debris,* ESA SP-587, European Space Agency, Paris, France, August 2005.

[3] See Barr, Z., "He Knew It Fell from the Sky," broadcast, Colorado Public Radio, April 14, 2011, available at http://www.cpr.org/article/He_Knew_It_Fell_From_The_Sky; and "Man finds part of Russian rocket in Colorado," video, 9News.com, April 14, 2011, available at http://www.9news.com/video/default.aspx?bctid=903246061001.

[4] NASA, "Russian Launch Vehicle Stage Reenters over U.S.," *Orbital Debris Quarterly News* 15(2):3, April 2011.

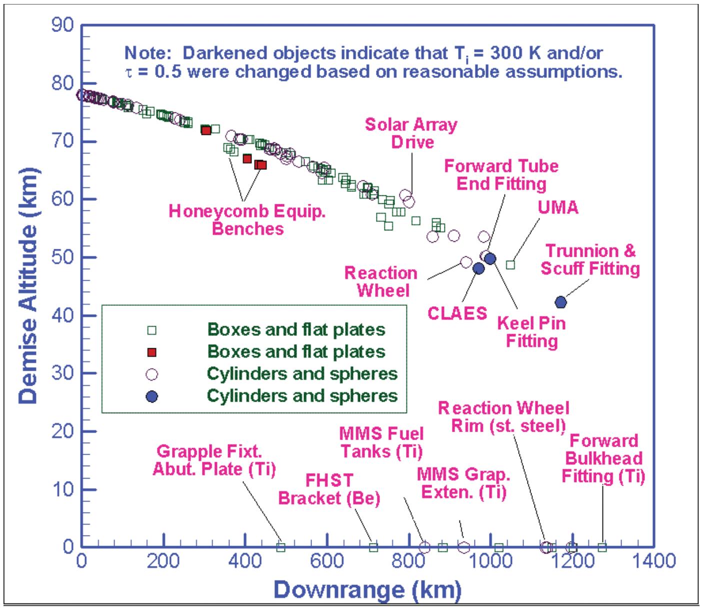

FIGURE 8.1 Depiction, using ORSAT, of the reentry disintegration of the Upper Atmosphere Research Satellite (UARS). The demise altitude versus downrange impact point is evaluated for major UARS components. SOURCE: Courtesy of NASA-JSC.

For each surviving object, a single point estimate is provided for the mass remaining along with its terminal velocity, thus producing a damaging effect on people on the ground as determined by its kinetic energy. The dispersion of multiple fragments surviving to the ground from a single object's disintegration provides an area over which the debris will potentially pose a hazard to people on the ground, which in turn produces a single probability of casualty on the ground for the reentry event. Despite the wide range of potential variations that could result in rentry, neither uncertainty estimates nor confidence bounds are provided for impact point, mass of surviving object, or probability of casualty.[4] Uncertainty information is required for management to be able to place this risk in proper perspective with others to guide decisions about direction of work and funding.

Finding: NASA's Object Reentry Survival Analysis Tool provides results as point estimates without confidence bounds or uncertainty estimates.

Recommendation: In regard to debris reentry risk, NASA should provide confidence bounds on and uncertainty estimates of the resulting risk levels for use in both the Debris Assessment Software and the Object Reentry Survival Analysis Tool.

ORSAT is developed by NASA and used only by Orbital Debris Program Office personnel, due to the complex model interfaces and complicated modeling processes portrayed. However, the ODPO has created a more conservative and simpler reentry demise module as part of DAS, which is available to the public. As indicated previously, if DAS determines that none of the material from a reentering piece of space hardware will survive to the ground, then this determination is sufficient to assure compliance with STD 8719.14. However, if DAS indicates that the reentry scenario is non-compliant, the situation may be reanalyzed using ORSAT, which provides

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[4] R.N. Smith, J. Dobarco-Otero, K.J. Bledsoe, and R.M. DeLaune, *User's Guide for Object Reentry Survival Analysis Tool (ORSAT)—Version 6.0,* JSC-62861, NASA Johnson Space Flight Center, Houston, Tex., January 2006.

a more detailed and accurate assessment as described above. ORSAT has been used numerous times, providing great utility to mission programs.[5]

The use of ORSAT and DAS for assessing the survivability of reentering debris will increase as debris continues to reenter and concerted efforts are made to remove derelict hardware from orbit. As with other model developments, NASA uses IADC deliberations to perform cross-program comparisons of ORSAT with ESA's equivalent model(s).[6] Although mathematical results for reentry object disintegration are found to be very similar between the two models, the inconsistent definition of "casualty" between ESA and NASA makes it difficult to easily compare results. ESA considers a "casualty" to be a person who is *killed* by a reentering object, whereas NASA (within ORSAT and DAS) considers a "casualty" to be a person who is *injured* by a reentering object. As a result, ORSAT is more conservative than the ESA reentry survival model; it predicts a higher probability of a "casualty" from the same reentry events. Updating ORSAT to provide the probabilities for both injury and death as standard outputs would require only a simple coding change.

Finding: The reentry hazard programs used by NASA and the European Space Agency to determine the risk to people on the ground from reentering debris differ in how those thresholds are defined. NASA's Object Reentry Survival Analysis Tool defines a "casualty" as personal injury, whereas ESA models equate a "casualty" with death.

Recommendation: NASA should update the Object Reentry Survival Analysis Tool so that it provides the probabilities of both injury *and* death as standard outputs.

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[5] For examples of the use of ORSAT by mission programs, see J.P. Rustick and W.C. Rochelle, *Reentry Survivability Analysis of GENESIS Spacecraft Bus,* LMSEAT 33557, December 2000; J.P. Rustick and W.C. Rochelle, *Reentry Survivability Analysis of Earth Observing System (EOS)—Aqua Spacecraft,* LMSEAT-33622, March 2001; R.N. Smith and W.C. Rochelle, *Reentry Survivability Analysis of Compton Gamma Ray Observatory (CGRO),* JSC-28929, NASA Johnson Space Center, Houston, Tex., March 2000; R.N. Smith, R.M. DeLaune, and J. Dobarco-Otero, *Reentry Survivability Analysis of the Genesis Spacecraft Bus for Off-Nominal Trajectories,* JSC-62665 Rev. A, NASA Johnson Space Center, Houston, Tex., August 2004; R.N. Smith and W.C. Rochelle, *Reentry Survivability Analysis of Earth Observing System (EOS)—Aura Spacecraft,* LMSEAT-33712, July 2001, p. 12; R.N. Smith, J. Dobarco-Otero, J.J. Marichalar, and W.C. Rochelle, *Tropical Rainfall Measuring Mission (TRMM)—Spacecraft Reentry Survivability Analysis,* JSC-29837, NASA Johnson Space Center, Houston, Tex., September 2002, p. 4; R.N. Smith, J. Dobarco-Otero, and W.C. Rochelle, *Reentry Analysis of Gamma-ray Large Area Space Telescope (GLAST) Satellite,* JSC-49775, NASA Johnson Space Center, Houston, Tex., July 2003, p. 6; R.N. Smith, K.J. Bledsoe, and J. Dobarco-Otero, *Reentry Survivability Analysis of the Hubble Space Telescope (HST),* JSC-62599, NASA Johnson Space Center, Houston, Tex., May 2004; R.N. Smith, J. Dobarco-Otero, and R.M. DeLaune, *Reentry Survivability Analysis of Shuttle External Tank Debris,* JSC-62683, NASA Johnson Space Center, Houston, Tex., December 2004; and R.N. Smith, J. Dobarco-Otero, and R.M. DeLaune, *Reentry Survivability Analysis of the Terra Satellite,* JSC-63042, NASA Johnson Space Center, Houston, Tex., June 2005, p. 3.

[6] W. Rochelle et al., "Results of IADC Reentry Survivability Benchmark Cases: Comparison of NASA ORSAT 5.0 Code with ESA SCARAB Code," presentation at the 17th IADC meeting, Darmstadt, Germany, October 1999.

9

Conjunction Assessment Risk Analysis and Launch Collision Avoidance

Today, satellite operators—including NASA—must launch and then maintain their satellites in a risky environment that is the result of a combination of threats. One of those threats is the presence of natural and artificial debris in the near-Earth space environment, and the increasing potential for high-impact events (e.g. on-orbit collisions) makes spacecraft even more vulnerable (Box 9.1).

Mitigating the risk of debris events to operational satellites requires different approaches based on the type of debris. Protecting against natural debris (meteoroids) must be addressed via passive techniques (e.g., shielding), since it is currently impossible to track these objects and predict their course to enable an operator to take evasive action. The same is true for small artificial debris, which cannot be tracked with today's space surveillance networks.

The U.S. Space Surveillance Network (SSN) can track objects only down to about 10 cm in LEO (below 2,000 km) and 1 m in geosynchronous Earth orbit (GEO). The Joint Space Operations Center (JSpOC) currently tracks more than 22,000 objects larger than these thresholds. NASA, however, estimates that half a million objects larger than 1 cm reside in LEO—the size object that some portions of the International Space Station (ISS) are shielded to withstand. Typical satellites are not shielded even this well, and untracked objects larger than 5 mm can cause substantial damage, with relative velocities as high as 15 km/s in LEO, but with an average relative velocity in LEO of about 10 km/s. The relative velocity for collisions in GEO is much smaller, with an average of 500 m/s. Until better space surveillance tracking capabilities are operational, the threat of collisions with these untracked objects cannot be mitigated. An upgrade to the current U.S. Air Force (USAF) Space Fence is planned, and Phase 2 is in progress. The new fence will more accurately track objects as small as 5 cm in diameter in LEO.

To mitigate the risk of collision with a cataloged object, NASA performs two processes. Conjunction assessment risk analysis (CARA; at GSFC for robotic spacecraft)/conjunction assessment (CA; at JSC for the ISS and the space shuttle) is the process performed for mitigating the risk of an operational satellite colliding with a cataloged object, and launch collision avoidance (COLA) is the process performed to try to prevent a collision with a cataloged object during launch.

CARA/CA

For objects that can be tracked, it is possible to make decisions to maneuver operational satellites (if they are able to maneuver) to reduce the chance of collision with a cataloged space object. CARA/CA is the effort to

BOX 9.1
On-Orbit Collision of Iridium 33 and Cosmos 2251

On February 10, 2009, the satellite communications company Iridium lost contact with one of its spacecraft, Iridium 33. Earlier that day, Iridium had received a prediction of a close approach of 584 m (1,916 ft) between Iridium 33 and another orbiting spacecraft, the non-operational Russian communications satellite Cosmos 2251. Iridium had received close approach reports before, and the one on February 10 was not particularly alarming or deemed a "top predicted close approach" compared to other predicted close-approach events for that week. Nevertheless, at the time the close approach was predicted to occur above northern Siberia, Iridium abruptly stopped receiving telemetry from its spacecraft.

The destruction of Iridium 33 was confirmed when the U.S. Space Surveillance Network (SSN) detected debris clouds in the orbits of both Iridium 33 and Cosmos 2251, marking the first payload-to-payload collision in the history of spaceflight. (See Figure 9.1.1.) The collision of Iridium 33 and Cosmos 2251 added an additional 2,181 trackable pieces of debris to the approximately 19,000 objects larger than 10 cm already in orbit in 2009.[1] (See Figure 9.1.2.) Today, more than 22,000 pieces of debris are being tracked,[2] plus an estimated population of approximately 500,000 particles between 1 and 10 cm, and more than tens of millions of particles smaller than 1 cm orbiting Earth.[3] Some of the debris from that collision has reentered Earth's atmosphere: as of May 2011, the SSN had cataloged 547 pieces of debris associated with Iridium 33 (down from 594 originally) and 1,488 pieces of debris associated with Cosmos 2251 (down from 1,587 originally).[4] Particles smaller than 10 cm are very difficult to track reliably with current capabilities.[5]

Iridium created its own collision analysis process during the initial development and launch phase of the Iridium constellation of satellites. Although the data available for tracking a satellite's position are the best the U.S. government can offer, those data were not designed to be used for conjunction analysis, although they are being used for that purpose today. Prior to the Iridium–Cosmos collision, Iridium had never made an on-orbit maneuver with one of its satellites in response to a close approach prediction. Between February 2009 and February 2011, Iridium made 41 collision mitigation maneuvers based on 46 close approach warnings;[6] however, all of these actions were integrated into normal constellation maintenance actions and so had little impact on Iridium operations.

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[1] NASA Orbital Debris Program Office, "Orbital Debris Frequently Asked Questions," available at http://orbitaldebris.jsc.nasa.gov/faqs.html#3.

[2] Government Accountability Office, *Space Acquisitions: Development and Oversight Challenges in Delivering Improved Space Situational Awareness Capabilities,* Report to the Subcommittee on Strategic Forces, Committee on Armed Services, House of Representatives, GAO-11-545, Washington, D.C., May 2011.

[3] NASA Orbital Debris Program Office, "Orbital Debris Frequently Asked Questions," available at http://orbitaldebris.jsc.nasa.gov/faqs.html#3.

[4] See T.S. Kelso, "Iridium 33/Cosmos 2251 Collision," updated May 13, 2011, available at http://celestrak.com/events/collision/.

[5] J. Lyver, NASA, presentation at the Workshop to Identify Gaps and Possible Directions for NASA's Micrometeoroid and Orbital Debris Programs, March 9, 2011, National Research Council, Washington, D.C.

[6] J. Campbell, Iridium, presentation at the Workshop to Identify Gaps and Possible Directions for NASA's Micrometeoroid and Orbital Debris Programs, March 9, 2011 National Research Council, Washington, D.C.

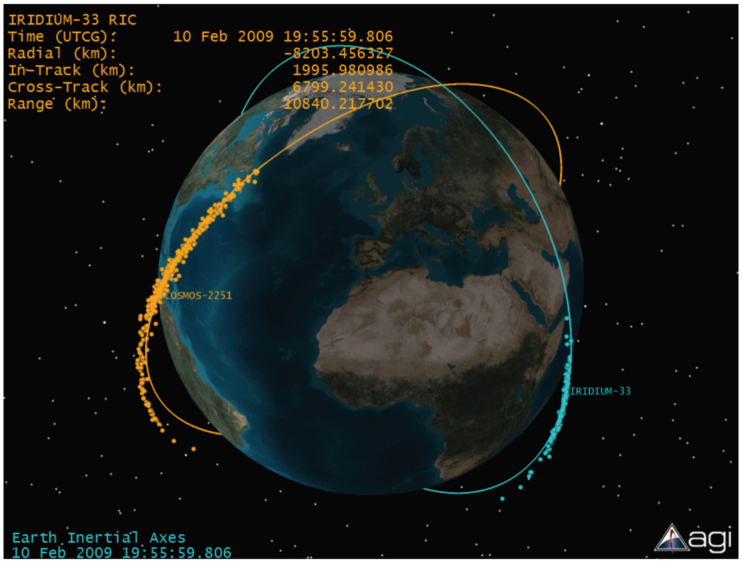

FIGURE 9.1.1 View of Iridium 33 and Cosmos 2251 orbits and debris from each spacecraft 180 minutes after their collision with one another. What should be one dot for each orbit is now thousands. SOURCE: Courtesy of T.S. Kelso, CelesTrak.com.

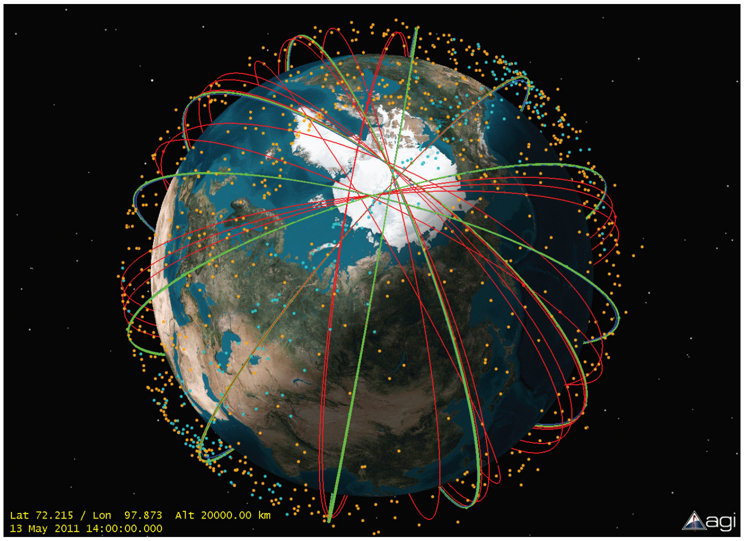

FIGURE 9.1.2 Screen shot from AGI Viewer 9 file of current Iridium constellation and collision debris clouds. SOURCE: Courtesy of T.S. Kelso, CelesTrak.com.

determine the orbits of all known objects relative to the operational satellite population in order to facilitate decision making regarding whether to take preemptive action to avoid potential collisions. To perform CARA/CA, a satellite operator must know not only the orbit of their satellites and the potential collision threats, but also the uncertainty associated with those estimated orbits. This information can then be used to determine future close approaches and flag those that exceed a certain threshold (e.g., range at closest approach or probability of collision). When a close approach is identified that exceeds the operator's threshold, the operator must know whether the potential threat is another operational satellite or a piece of debris (such as a spacecraft fragment or a dead satellite). If the potential threat is an operational satellite, which may be capable of maneuvering, the operator will also need to know how to contact the other operator to collaborate on a course of action and ensure that they do not unwittingly make the situation worse.

The computation of the probability of collision, P_c, is a critical part of CARA because it is that value that is the primary basis for the decision about whether or not to make a collision avoidance maneuver. The two key assumptions in the calculation of P_c for objects in LEO are that (1) the relative motion of the two objects at conjunction is rectilinear, and (2) the position uncertainty distributions of the objects at conjunction are Gaussian. The first assumption is valid as the time interval of concern is about 0.25 s. The uncertainty (covariance) at conjunction is obtained by propagating the covariance from epoch (i.e., the time when covariance was calculated) to the conjunction time. This propagation is based on a linearization of the equations of motion about the reference (estimated) orbit. CARA is performed for conjunctions 6 to 7 days into the future. There is evidence that the Gaussian assumption may not be valid beyond 2 to 3 days into the future[1] as a result of neglected nonlinearities in the propagation of the covariance. The quantitative impact of this non-Gaussian behavior on P_c is not known.

NASA currently performs CARA for about 50 missions as part of normal satellite operations and CA for the ISS and previously for the space shuttle. Although NASA and its partners (e.g., ESA) have the best data for those 50 satellites—including planned maneuvers—they do not have an independent means to perform orbit determination for the thousands of other objects that might pose a collision threat to their satellites. These data are available only by means of the JSpOC, but the data are not released to NASA or other satellite operators (for several reasons, including national security), with the exception of two-line element sets (TLEs), which are released only for the public catalog (more than 16,000 objects) and not for objects that have an unknown source (another ~7,000 objects, which still pose a threat).

Although TLEs are available to NASA and the public, several problems exist with these data. First, to propagate these data correctly, access is required to the same orbital model (Simplified General Perturbations 4 or SGP4) used to generate the data. However, the Air Force Space Command (AFSPC) has marked this model as "Export Controlled" and has not released it to the public since 1980. Without the changes made to this model since then, it is possible to have errors on the order of 1,000 km in GEO.

Second, although these data are generally good enough for their intended purpose to maintain tracking by the U.S. Space Surveillance Network (SSN), the associated uncertainties (which are not quantified or provided with the TLE data, but are on the order of hundreds of meters to kilometers in LEO and kilometers to tens of kilometers in GEO) contribute to high false-alarm rates and discourage efforts to perform CARA. The large uncertainties are the result of the nature of the SSN tracking that does not take into account maneuvers when computing the TLEs. It is not unusual for it to take a week or more to detect maneuvers and update the associated orbits. It is also common to see objects cross-tagged (switched) within the GEO population, since the noncooperative tracking has no independent way to know which object is which.

The JSpOC also has special perturbations (SP) data that are generally considered to have higher accuracy, but that are collected by the same network and processed with the same algorithms but using a higher-fidelity force model. These data do not consider the effects of maneuvers and can be impacted by cross-tagging. Also, although SP data do include covariance information, it is generally agreed that the amount is too small (meaning that the uncertainty is large) as a result of the way the SSN sensor observations are collected and sent to the JSpOC for

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[1] C. Sabol, T. Sukut, K. Hill, K.T. Alfriend, B. Wright, and P.W. Schumacher, "Linearized Covariance Generation and Propagation Analysis via Simple Monte Carlo Simulations," Paper No. AAS 10-134, AAS/AIAA Space Flight Mechanics Conference, San Diego, Calif., February 14-17, American Astronautical Society, Springfield, Va., 2010.

processing, and the method used for determining the orbits from the observations. In addition, the probability of collision, P_c, is very sensitive to errors in the uncertainty near the threshold of the decision to maneuver, $10^{-4}<P_c<10^{-3}$. An error of a factor of two in the uncertainty can change the probability of collision by at least two orders of magnitude.[2] Release of the SP data occurs under very limited circumstances, and it would have to be released in near-real time for it to be useful to NASA. Consequently, NASA must rely on the JSpOC to screen its satellites and report close approaches based on what the JSpOC deems reasonable. Currently, the JSpOC looks out 5 to 7 days ahead, but reports only close approaches within 1 km total and 200 m radial for LEO objects and 5 km total for GEO objects 3 days ahead. The 3-day time horizon leaves little time for an operator to attempt to get better tracking data, make the necessary decision regarding collision avoidance measures, and then plan and conduct a maneuver if necessary.

The JSpOC provides only a state vector and covariance in its Orbit Conjunction Messages (OCM) to NASA when the JSpOC identifies a conjunction, but it is unclear where these data come from. Originally, the source was the SP data used in the analysis. However, even when it takes in ephemeris data from NASA, the JSpOC does not provide that information back in the OCM. Therefore, when the JSpOC does not use ephemeris data with maneuvers, it can report false conjunctions or miss real ones. The overall lack of transparency in the data and underlying processes serves to undermine confidence in the entire CARA process and increases the risk of collision for NASA missions.

NASA currently has little or no control over these data restrictions or the JSpOC processes used in the conjunction assessments. One potential recourse would be to participate in the non-profit Space Data Association's Space Data Center (SDC), a collaborative effort in which 20 commercial and civil operators now share data on 300 satellites with the goal of improving the safety of space operations, including improving CARA. All SDC participants provide ephemeris for their satellites—including planned maneuvers—to be used in conjunction screening. Operator ephemeris data has been shown to be an order of magnitude more accurate than the SSN data (TLE data), due to its use of active tracking observations. That reduces the uncertainty volume by three orders of magnitude and helps make the problem much more manageable. In addition, the inclusion of maneuvers and lack of cross-tagging (since the satellite operators know which satellite is which) greatly reduce the number of false alarms and the chance of unnecessary or misguided actions. However, these data are available only for the satellites of the companies participating in the SDA. Hence, participation in the SDA can improve CARA only with the satellites participating in the SDC, but even with these satellites a probability of collision cannot be performed because covariance information is not provided.

Understanding Risk

It is important to understand how risk guides CARA efforts. Although the current CARA process and the data on which it relies can be improved, only a regular exercise of the process and identification of the shortcomings will make it an effective decision-making tool. As emphasized in *An Introduction to Factor Analysis of Information Risk*, "You can't effectively and consistently manage what you can't measure, and you can't measure what you haven't defined."[3] Without a clear understanding of how risk is defined, it cannot be appropriately managed.

Risk is the combination of the probability of an event with the consequences of that event. For example, the probability of a satellite being hit by a 1-mm piece of debris may be higher than its being hit by another satellite, but in the latter case the consequences for the survival of the satellites and the effects on the space environment would be worse (as demonstrated in the Iridium–Cosmos collision). Likewise, the consequences of not attempting to avoid a predictable collision could cause serious negative reactions among stockholders of a satellite operator or among U.S. taxpayers and Congress, who fund NASA's budget. Reactions would be particularly bad if it were

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[2] K.T. Alfriend, M.R. Akella, D.-J. Lee, M.P. Wilkins, J. Frisbee, and J.L. Foster, Probability of collision error analysis, *International Journal of Space Debris* 1:21-35, 1999.

[3] J.A. Jones, *An Introduction to Factor Analysis of Information Risk (FAIR)*, draft, Risk Management Insight, Columbus, Ohio, 2005, available at http://riskmanagementinsight.com/media/documents/FAIR_Introduction.pdf, accessed July 20, 2011.

discovered that the problem were manageable at low cost, but that the satellite operator chose to ignore the risk or that its efforts were confounded by unnecessary bureaucratic obstacles.

NASA and the U.S. National Space Policy

Under the new 2010 National Space Policy, NASA is required to take efforts to preserve the space environment—specifically, to "pursue research and development of technologies and techniques . . . to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment."[4] NASA can and must perform CARA on its satellites to reduce the hazard to other satellites or the risk of creating more debris. NASA may take collaborative action—with organizations like the new Space Data Association—to promote transparency in CARA, promote best practices, and further reduce the likelihood of avoidable collisions that could impact national or economic security and further degrade the near-Earth space environment. These actions are all consistent with U.S. national space policy and would help NASA to more effectively and efficiently conduct CARA to support NASA space missions.

Finding: The computation of the probability of collision for use in an assessment of risk requires the uncertainty parameters in the orbits of the two objects at conjunction, and assumes that these uncertainties are represented by a Gaussian distribution. Research has shown that the uncertainty distribution typically is Gaussian for several days, but when propagating for more than 2 to 3 days it may no longer be Gaussian. In addition, the uncertainties provided by the JSpOC are known to be usually too small, and the probability of collision can be very sensitive to errors in the size of the uncertainty.

Recommendation: NASA should develop a research plan for (1) assessing the impact of inaccuracy in the uncertainty on computations of the probability of collision and on the ensuing risk assessment, and (2) improving the accuracy of the computation of the probability of collision, given the presence of these uncertainty errors.

LAUNCH COLLISION AVOIDANCE

Launch collision avoidance (COLA) (see item 16 in Box 12.1, Chapter 12) is the process of actively screening for potential collisions between a launch vehicle and known, tracked, on-orbit objects from liftoff through the end of the launch phase and subsequently taking action to avoid any unacceptable conjunctions. Range safety COLA applies to crewed or crewable space objects, and mission assurance COLA applies to uncrewed objects. COLA is performed by the Launch Services Program (LSP) at Kennedy Space Center. COLA is not required by LSP; it is performed at the request of the customer. GSFC has requested COLA for all of its missions for the primary purpose of protecting orbiting assets, not the satellite being launched. USAF instructions mandate the operational implementation of launch conjunction assessment and collision avoidance at AF-controlled ranges, and avoidance of crewed conjunctions is mandatory for safety.

LSP obtains launch COLA support from The Aerospace Corporation, which uses a probability-based tool called "Collision Vision" that has extensive heritage on NASA, USAF, and NRO (National Reconnaissance Office) launches. The use of the tool requires a trajectory ephemeris and covariance at key trajectory event milestones from the contractor. The launch COLA analysis is performed for all separated bodies up through 100 minutes after separation. The primary issues with COLA include the following:

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[4] National Space Policy of the United States of America, June 28, 2010, available at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf, accessed July 6, 2011.

- How long should screening last? The AFI 91-217 requires launch COLA screening until the objects have entered the space object catalog,[5] and this process can take several days. However, due to the large uncertainties in the launch dispersions (deviations from a planned trajectory), the COLA methodology cannot be reasonably used except for a few orbits after launch. This leaves a large gap in time.
- Does one use probability-based screening or miss-distance screening? The probability of collision is a function of the miss distance, the direction of the miss distance relative to the trajectory, and the uncertainty. Thus, one cannot select a probability of collision and obtain a minimum miss distance. The problem with probability-based screening is that the large dispersions with the launch vehicle trajectories usually result in a probability of collision of less than 10^{-5}, and this risk is much lower than other risks usually associated with launch activities. Of 676 conjunctions analyzed by NASA, only 1 percent had probabilities of collisions greater than 10^{-5}. LSP currently uses the probability-based approach.

> **Finding: The large uncertainties in the launch dispersions (deviations from a planned trajectory) that yield a probability of collision of less than 10^{-5} translate to a very low return on investment in launch collision avoidance (COLA), and funds could probably be used more effectively in some other area of debris mitigation. However, in the event of a collision during launch, the political realities of potentially having done nothing probably mean that the use of COLA needs to continue, especially for crewed launches.**

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[5] B. Beaver, “Launch Collision Avoidance for MASA ELV Missions,” presentation to the Committee for the Assessment of NASA’s Orbital Debris Programs, January 19, 2011, National Research Council, Washington, D.C.

10

Spacecraft Anomalies

Whether the NASA MMOD programs focus on protecting the space environment or the spacecraft, monitoring, reporting, and analysis of satellite anomalies are of vital importance. Particulate-induced anomalies could provide valuable validation of environment characterization of objects within critical size ranges (5 mm to 10 cm for debris and 10^{-11} g for meteoroids) and velocities (7 km/s for debris, up to 72 km/s for meteoroids if in bound solar orbit), as well as a better understanding of operational effects owing to particulate impacts.

Satellite anomalies are mission-degrading or mission-terminating events affecting on-orbit operational spacecraft. However, it is not normal procedure to provide information on these anomalies to the public or even to other offices within the same organization, for to a variety of reasons: limited staff for reporting and analysis, concerns about system reputation, desire to protect proprietary information, uncertainty in the meaning or cause of the events, national security, and so on. Depending on their severity, a program operations philosophy, and an available staff, anomalies are recorded and analyzed to some degree. Individual operational satellite programs, such as Iridium, Defense Meteorological Satellites Program, and others, use such information as a means to (1) assess system performance, (2) determine potential changes in operations, or (3) diagnose the cause of an event.

There is no standard nomenclature for describing system symptoms associated with anomalies or how they are recorded, shared, resolved, or stored. There is no standard approach to prioritizing steps in a process for addressing an anomaly, including recording, resolution, and/or determination of cause. Many system operators are much more concerned about getting their satellite back into operation than about determining the cause of a failure. Repeat failures often get examined much more rigorously.

Typically, the following causes of anomalies are considered: routine failures of parts, electrostatic discharge, single-event upset, command error, particulate impact, and unknown. Unfortunately, there is no standard resolution process to determine the cause of an anomaly. The process of determining a cause is unreliable, and the degree of confidence applied to any one cause is minimal. “Unknown” is attributed to the vast majority of anomaly cases, since it is so difficult to determine exactly what happens in space without dedicated instrumentation to provide insights from on-orbit encounters that adversely affect satellite operations. There may be times when an “unknown” is erroneously attributed to a meteoroid or orbital debris event. Or there may other times when additional data indicates a high probability that the failure was caused by an MMOD event (see Box 10.1).

From a flight safety perspective (i.e., protecting the spacecraft), determining the cause of anomalies in space is important to better assess how the system will continue to function and how future systems might perform. From an environment characterization perspective, accurate accounting of environment-based anomalies provides

BOX 10.1 Damage Analysis

After nearly 7 years of service providing power to the International Space Station (ISS), the P6 solar photovoltaic power module (P6) was moved from its original location on the Z1 truss to its permanent location on the port outboard truss of the ISS. When the crew of the STS-120 mission redeployed the solar array in its new location in 2007, the array started to tear in two places as shown in Figure 10.1.1, forcing the crew to stop deployment at 90 percent of completion.

If this had been a robotic spacecraft, the only clues available to ground controllers would have been those provided by telemetry to guide their analysis of what had caused the failure, with the result perhaps being a conclusion that the failure was only mechanical, or a design flaw.

However, the STS-120 astronauts were able to cut away the frayed guidewire that caused the tear in the panels and bring it back to Earth for analysis. NASA scientists examined the frayed end of the guidewire with a scanning electron microscope, discovering damage to it in the form of melting that was characteristic of fusing from the impact of a meteoroid or orbital debris. Further examination using a narrow-focus electron microprobe and energy dispersive x-ray spectrometer to analyze the chemical elements in the impact zone resulted in the conclusion that the damage was caused by orbital debris, not a meteoroid.

Currently, most robotic spacecraft do not have systems sophisticated enough to provide the kind of detailed information necessary to say conclusively that an MMOD impact caused a failure of some part or system. However, clues that MMOD may be a cause are found by correlating a failure with data on the environment at the time (e.g., the spacecraft passed through a meteor shower or an orbit known for large amounts of debris), or an unexplained change in momentum. In this case, NASA's astronauts, and scientists, were fortunate to retrieve a piece of hardware directly involved in damage to the spacecraft and to be able to thoroughly examine that hardware in the lab. Without it, they would not have had all of the pieces of the puzzle to solve this mystery.[1]

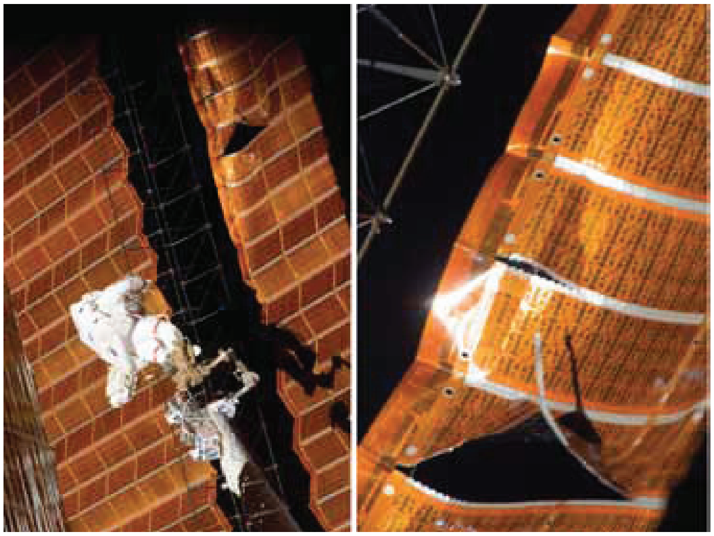

FIGURE 10.1.1 Two tears approximately 30 cm and 90 cm long in the P6 solar array wing 4B after an attempt to redeploy the array during the STS-120 mission. SOURCE: Courtesy of NASA, from D. Ross, E. Christiansen, and D. Lear, MMOD damage to the ISS solar array guidewire, *Orbital Debris Quarterly News* 15(1):4, January 2011.

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[1] D. Ross, E. Christiansen, and D. Lear, MMOD damage to the ISS solar array guidewire, *Orbital Debris Quarterly News* 15(1):4, January 2011.

another means to help characterize the environment and validate environment models. It is possible that impacts from debris and meteoroids of sizes as small as 100 microns and as large as several centimeters might adversely affect operational systems without the satellite owner being able to determine that an impact had occurred, other than by evaluating how the system functioned after the impact.

Figure 10.1 depicts generally how the orbital debris population presents a challenge from the perspective of collision risk and environment characterization. Basically, the smallest debris objects are only characterized by returned samples; their impact is not normally a concern since the hazard can be largely managed by shielding and inherent design; yet the flux (impacts per exposed area over time or probability of collision) of debris of this size is the highest.

In the debris population, the largest objects are the least numerous; however, the potential consequence, if an impact were to occur, is catastrophic. These objects are cataloged and so potentially can be avoided. The medium size range, approximately 5 mm to 10 cm for orbital debris, is the most difficult to characterize, with only episodic radar measurement campaigns contributing to knowledge of the environment, yet the risk (probability of collision times consequence) may be the greatest in this size range.

Undoubtedly, impacts with debris in the medium size range should be occurring much more often than collisions between trackable objects. It is this "residual risk" that may be better characterized by clearer, consistent recording, analysis, reporting, and sharing of satellite anomalies, since such orbital encounters cannot be observed from the ground. However, even the lower end of the range of sizes at which particles might be causing spacecraft anomalies is highly uncertain because of the wide variety of space system designs encountered, varying impact speeds and directions, and a wide range of particle characteristics. These uncertainties hold for both meteoroids and orbital debris.

For orbital debris, the size threshold for particles likely involved in anomaly-inducing impacts in LEO is significantly different from the threshold in GEO, because impact velocities are much greater in LEO and the smallest object regularly cataloged in GEO is 1 m, compared with but 10 cm in LEO. As a result, the anomaly resolution process will be slightly different in the two orbits, adding yet another complexity to the analysis of satellite anomalies.

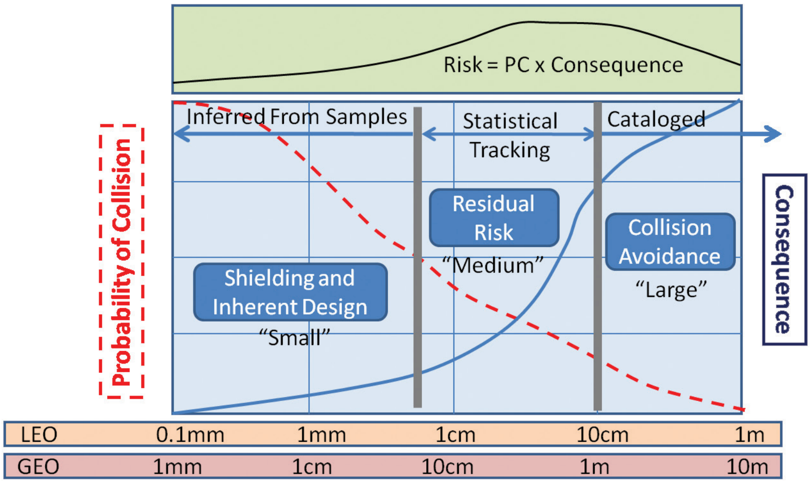

FIGURE 10.1 Risk versus debris impactor size. The debris sizes of concern in these categories are roughly offset by a factor of 10 between low Earth orbit (LEO) and geosynchronous Earth orbit (GEO). A compilation of satellite anomalies would provide insight into the environment and subsequent effects that might potentially pose the greatest overall risk to current spacecraft.

For the natural particulate environment, it is critical to determine just how smaller, faster meteoroids might create mission-degrading and mission-terminating failures. Significant debate and ongoing research are focused on the possibility that particulate-catalyzed electrical failures may contribute measurably to the compendium of satellite anomalies. Strong data from experimentation show that plasma is produced during a hypervelocity impact event. At meteoroid velocities such free charges near a spacecraft might be expected to cause electrostatic discharge (ESD) and electromagnetic pulse (EMP) events (for additional detail on these phenomena, see Chapter 4, "The Meteoroid Environment and Its Effects on Spacecraft"). In addition, ground-based experiments have shown that significant plasma is produced when a particle impacts a satellite even at speeds typically associated with orbital debris (around 7 km/s). The electrical anomalies resulting from either a debris or a meteoroid impact remain poorly characterized.[1]

Although it will be difficult to determine the contribution to anomalies from meteoroids versus orbital debris, it is important to gain an understanding of that balance to provide a forcing function for future research and operational procedures. This issue is also discussed in Chapter 3, "Orbital Debris Modeling and Simulation."

Just as the Orbital Debris Program Office works to significantly increase measurements of the sub-5-mm population through returned samples and of the 1- to 10-cm population through Haystack measurement campaigns, developing standard processes for recording, analyzing, reporting, and sharing satellite anomalies will provide a rich source of information not only on the environment flux but also on the effects on satellite systems of impacts by particles in the 5 mm to 10 cm size range.

An examination performed on a limited set of records for the past 20 years for satellite anomalies identified discrepancies in the available data that may make any post facto analysis of limited use, and it is essential that NASA now prepare for the future and establish a means to change this situation going forward. Many physical phenomena are reported indirectly but are crucial for determining the impactor that caused an anomaly: sudden pointing direction change, sudden drop in current from solar arrays, discrete voltage changes on instruments or power system, and so on can all be used to diagnose an anomaly.

Previous analyses have focused on the probability of impact equating to a probability of physical damage, yet it is possible that an impact itself may not be the only causative mechanism for failure. The impact may directly create an EMP or be the catalyst for an electrostatic discharge, as hypothesized above for fast meteoroids.

The difficult chore of writing and promulgating a standard process for satellite anomaly recording, analyzing, reporting, and sharing could leverage the successful migration of debris mitigation guidelines into international standards. This new effort can also leverage the current outreach and international dialog in which ODPO participates at the Inter-Agency Space Debris Coordination Committee, the United Nations, and other such organizations.

Databases already exist that contain spacecraft anomalies. An example is the Aerospace Corporation's Space System Engineering Database (SSED).[2] The SSED provides valuable data related to satellite failures and anomalies; however, it does not provide sufficient coverage or fidelity to permit the development of causative relationships with MMOD particulate environments. Attempts to use existing databases have produced results suggesting that a statistical relationship might exist between certain types of failures and the MMOD environment, but its insufficiency makes the information in the databases conclusive.[3]

Development of standard processes for characterizing satellite anomalies will also provide a database that will complement the continued measurement campaign in this size range, which in turn will support the continued refinement of MEM, ORDEM, and BUMPER. Predicted flux levels of orbital debris in the 5 mm to 10 cm size range and for meteoroids (10^{-11} g) in the 100 μm to 1 cm size range can be correlated with the actual number of satellite anomalies, creating a tighter linkage between environment definition and satellite operations.

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[1] See D.A. Crawford, and P.H. Schultz, Electromagnetic properties of impact-generated plasma, vapor and debris, *International Journal of Impact Engineering* 23:169-180, 1999; and Burchell et al., 1996.

[2] See J.F Binkley, Aerospace Corporation, "The Space System Engineering Database (SSED)," demonstration, available at http://klabs.org/mapld04/tutorials/mishaps/intro_aerospace.htm.

[3] D. McKnight, W. Riley, I. Shukry, and A.Shukry, Correlation of spacecraft anomalies to the debris environment, *Proceedings of SPIE* 2813:185-196, 1996.

Finding: Spacecraft anomalies are a direct measurement of both the state of the particulate environment in space and the adequacy of a spacecraft design. However, no formal recording, analyzing, sharing, and reporting procedures exist to take advantage of data on spacecraft anomalies despite that data's potential as valuable information about particulates in a critical size range that is typically not sampled continuously.

Recommendation: NASA should initiate a new effort to record, analyze, report, and share data on spacecraft anomalies in order to better quantify the risk posed by particulates too small to be cataloged yet large enough to disrupt spacecraft operations. The results of this effort would provide general insights into the effects of meteoroids and orbital debris on operational space systems. Eventually, this effort could provide data to upgrade current MMOD models—the Meteoroid Environment Model, Orbital Debris Environment Model, and BUMPER.

11

Issues External to NASA

INTERAGENCY COOPERATION

The guideline known as the 25-year rule,[1] which, as mentioned elsewhere in the report, seeks to restrict the post-operational life of objects in space to no more than 25 years, is contained in the *U.S. Government Orbital Debris Mitigation Standard Practices*[2] and NASA Technical Standard 8719.14.[3] It could be considered a professional standard practice. However, the fact that waivers are sometimes granted at various stages of mission planning calls this status into question.

The 25-year rule is not a "rule" in any legal sense, with one exception.[4] NASA recognizes this fact in its Procedural Requirements.[5] Under U.S. federal law, to be a "rule"—that is, a regulation that is legally binding on

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[1] The "25-year rule" is a guideline under consideration by an international organization the Inter-Agency Space Debris Coordination Committee (IADC), and is described in its "IADC Space Debris Mitigation Guidelines" released in 2002 and revised in 2007. The "rule" encourages entities with objects in low Earth orbit to ensure that their spacecraft and/or launch hardware are in an orbit that will decay and cause said object to reenter Earth's atmosphere within 25 years to mitigate the creation of more orbital debris. Although it may seem as though the IADC has formally adopted the rule, the 2007 revision notes that the "IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit." See http://www.iadc-online.org/Documents/Docu/IADC_Mitigation_Guidelines_Rev1_Sep07.pdf.

[2] The first practice is that "[e]ach instance of planned release of debris larger than 5 mm in any dimension that remains on orbit for more than 25 years should be evaluated and justified on the basis of cost effectiveness and mission requirements." The second practice is to "[l]eave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission." See NASA, *U.S. Government Orbital Debris Mitigation Standard Practices*, Section 4-1.a, available at http://orbitaldebris.jsc.nasa.gov/library/USG_OD_Standard_Practices.pdf.

[3] NASA, *Process for Limiting Orbital Debris,* NASA-STD-8719.14 (with Change 4), NASA, Washington, D.C., 2009, available at http://www.hq.nasa.gov/office/codeq/doctree/871914.pdf.

4 The FCC adopted the 25-year requirement as part of its notice and comment proceeding adopting orbital debris mitigation rules. *In the Matter of Mitigation of Orbital Debris*, Second Report and Order, 19 FCC Rcd 1157, paragraphs 84-85 (2004). See http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-130A1.pdf; Federal Register publication, 69 FR 54581, 54585 (September 9, 2004).

[5] "Note: It is recognized that NASA has no involvement or control in the design or operation of Federal Aviation Administration (FAA)-licensed launches or foreign or Department of Defense (DOD)-furnished launch services, and, therefore, these are not subject to the requirements in this NPR for the launch portion. This currently applies to Commercial Orbital Transportation Services (COTS), International Space Station (ISS) Commercial Resupply Services (CRS), and some NASA payloads for which unique launch services have been or plan to be acquired; e.g., Geostationary Operational Environmental Satellite (GOES-O), James Webb Space Telescope (JWST), and Lunar Atmosphere and Dust Environment Explorer (LADEE). Such launches are under the authority of other federal agencies (FAA or DOD) or foreign governments for direction and compliance [with] applicable orbital debris requirements. The payloads of such missions, e.g., COTS and CRS orbital vehicles and GOES-O, JWST, and LADEE spacecraft, that have a NASA involvement in the design and operation, are subject to the requirements of this document and process. It is intended that COTS and CRS launch vehicle stages or spacecraft carrying NASA cargo, that will be in the proximity of the ISS or

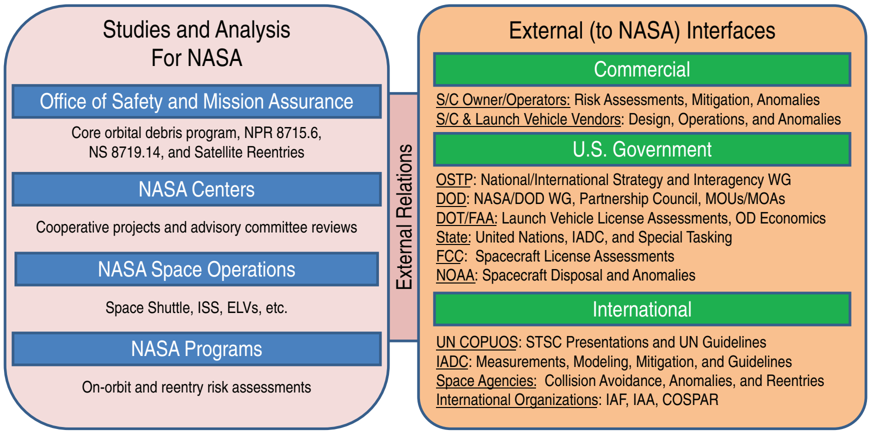

FIGURE 11.1 Interfaces external to NASA for addressing MMOD issues.

U.S. entities—it must go through the well-established formal rule-making process required by the Administrative Procedure Act (APA),[6] a process that applies to both federal executive departments and independent agencies. Absent this process, there is no legally binding rule.

It can be expected that the 2010 National Space Policy will likely increase demands placed on NASA's meteoroid and orbital debris (MMOD) programs. It can also be expected that clear rules will facilitate the interagency process needed to meet this demand (see Figure 11.1 for a diagram of the current interagency structure for addressing MMOD issues). Under the heading of "Preserving the Space Environment and the Responsible Use of Space," the policy states that the "United States shall . . . [r]equire the head of the sponsoring department or agency to approve exceptions to the United States Government Orbital Debris Mitigation Standard Practices and notify the Secretary of State."[7] This language implies a nascent process relevant to the U.S. standard practices including the 25-year rule. However, it still only states policy. As a national policy, it is a substantial statement of guiding authority. Nonetheless, it still does not rise to the level of the APA rule-making process.

Finding: NASA's Orbital Debris Mitigation Standard Practices, including the "25-year rule," and NASA's Procedural Requirements for Limiting Orbital Debris do not uniformly apply to non-NASA missions, launches, and payloads.

Recommendation: NASA should continue to engage relevant federal agencies as to the desirability and appropriateness of formalizing NASA's Orbital Debris Mitigation Standard Practices, including the "25-year rule," and NASA Procedural Requirements for Limiting Orbital Debris as legal rules that could be applicable to U.S. non-NASA missions and private activities.

INTERNATIONAL COOPERATION

There are multiple sets of existing guidelines concerning orbital debris, none of which are legally binding. They include those issued by NASA, the European Space Agency (ESA), the Inter-Agency Space Debris Coordination

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could leave debris near ISS orbit, would be reviewed per the requirements in this document as a part of the approval process to approach the ISS." See NASA, *NASA Procedural Requirements for Limiting Orbital Debris,* NPR 8715.6A (with Change 1), Office of Safety and Mission Assurance, NASA Johnson Space Center, Houston, Tex., May 14, 2009, p. 5, available at http://orbitaldebris.jsc.nasa.gov/library/NPR_8715_006A.pdf.

[6] U.S. Code §§ 500–596, P.L. 79-404.

[7] *National Space Policy of the United States of America*, June 28, 2010, pp. 7-8, available at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf, accessed July 6, 2011.

Committee (IADC), and the United Nations (UN).[8] The IADC guidelines were presented to the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS) Scientific and Technical Subcommittee (STSC) in February 2003. The guidelines were used by the STSC as a basis for UNCOPUOS's formulation of its own space debris mitigation guidelines, which were ultimately endorsed by the UN General Assembly (UNGA)[9] in Resolution 62/217 on December 22, 2007. The UNGA acknowledged that the IADC Space Debris Mitigation Guidelines "reflect[ed] the existing practices as developed by a number of national and international organizations"[10] while encouraging other member states to likewise adopt and implement the guidelines in domestic regulations.

The UNCOPUOS guidelines are very similar, but not identical, to the IADC guidelines. "The UN COPUOS and IADC guidelines are couched in the form of seven guidelines containing general recommendations to be implemented by States primarily through national legislation, regulations, and/or policy directives."[11] The IADC and UNCOPUOS guidelines differ in objective, scope, applicability, and terms and definitions, as well as mitigation plans (Table 11.1). These differences will provide opportunity for conflicting views of what is permissible and possible. There is tension between the various guidelines and their influence on nations. A major issue is whether implementing one set or another will impose costs on nations that choose to abide by them. Therefore, it is the position of some nations that costs ought to be borne by the nations that created the debris and that any accepted debris guidelines should be established on a fault-based system.[12]

The IADC is "an international governmental forum for the worldwide coordination of activities related to the issues of man-made and natural debris in space" whose "primary purposes . . . are to exchange information on space debris research activities between member space agencies, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperative activities, and to identify debris mitigation options."[13] Its members are the space agencies[14] of 12 space-faring nations.[15] The IADC is also the voluntary organization that advocated the IADC guidelines and brought them through an international political process.

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[8] United Nations Committee on the Peaceful Uses of Outer Space, *Towards Long-term Sustainability of Space Activities: Overcoming the Challenges of Space Debris, A Report of the International Interdisciplinary Congress on Space Debris,* Scientific and Technical Subcommittee, 48th Session, Document A/AC.105.C.1/2011/CRP.14, United Nations, New York, N.Y., February 3, 2011, p. 27.

[9] United Nations (UN), *Report of the Committee on the Peaceful Uses of Outer Space,* General Assembly Official Records, 62nd Session, Supplement No. 20, Document A/62/20, United Nations, New York, N.Y., 2007, paragraphs 117 and 118 and annex. The UN General Assembly in its resolution endorsed the Space Debris Mitigation Guidelines of COPUOS in 2007. See UN, "International Cooperation in the Peaceful Uses of Outer Space," General Assembly Resolution 62/217, UN General Assembly Official Records, 62nd Session, Agenda Item 31, Document A/RES/62/217, UN, New York, N.Y., January 10, 2008, paragraph 26.

UN General Assembly resolutions that do not address internal UN matters are nonbinding with the status of recommendations which member-nations have no formal obligations to obey. UN Charter, Articles 10 and 14.

[10] United Nations, "International Cooperation in the Peaceful Uses of Outer Space," January 10, 2008, paragraph 27.

[11] United Nations Committee on the Peaceful Uses of Outer Space, *Towards Long-term Sustainability of Space Activities: Overcoming the Challenges of Space Debris, A Report of the International Interdisciplinary Congress on Space Debris,* 2011, p. 27.

[12] Typical of this view is the one expressed by Belgium that a fault standard ought to be applied to any orbital debris guidelines or principles. See J.I. Gabrynowicz, National Center for Remote Sensing, Air and Space Law, University of Mississippi School of Law, "Unpublished notes re: UNCOPUOS LSC AM Session," on file with author, April 1, 2011.

[13] Inter-Agency Space Debris Coordination Committee website, available at http://www.iadc-online.org/index.cgi.

[14] For ease of discussion, the word "agencies" is used to refer collectively to centers, administrations, and organizations. Technically, under the national law of the nations in which they exist, these are different legal entities with different legal personalities, rights, responsibilities, and obligations. The reason that a particular nation chooses to establish a particular kind of entity is relevant to its national interests. However, for the limited purposes of this study, it is less relevant and the distinctions are not addressed. However, in the future there could be activities and situations in which the precise legal personality of an entity may be relevant.

[15] The IADC's members are:

- ASI (Agenzia Spaziale Italiana)
- CNES (Centre National d'Etudes Spatiales)
- CNSA (China National Space Administration)
- CSA (Canadian Space Agency)
- DLR (German Aerospace Center)
- ESA (European Space Agency)
- ISRO (Indian Space Research Organisation)
- JAXA (Japan Aerospace Exploration Agency)
- NASA (National Aeronautics and Space Administration)
- NSAU (National Space Agency of Ukraine)

TABLE 11.1 Inter-Agency Space Debris Coordination Committee (IADC) and United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) Space Debris Mitigation Guidelines

	IADC Guidelines[a]	UNCOPUOS Guidelines[b]
International consensus	Guidelines offer consensus of IADC members (space agencies, not nation-states).	In Resolution A/Res/62/217 on December 22, 2007, the UN General Assembly endorsed, but did not adopt, the UNCOPUOS Space Debris Mitigation Guidelines, which, as previously noted, relied in great part on the input of the IADC. The endorsed UN guidelines are very similar, but are not identical, to the IADC guidelines.
Objective	A main objective of the IADC guidelines is to provide measures that limit the generation of space debris in the environment.	The UNCOPUOS guidelines endorse mitigation recommendations for the safety of Earth and space missions. It does not address environmental protection.
Scope	The scope of the IADC guidelines is four-fold: (1) limitation of debris released during normal operations, (2) minimization of the potential for on-orbit breakups, (3) post-mission disposal, and (4) prevention of on-orbit collisions.	The UNCOPUOS guidelines specifically divide the space debris issue into two categories: (1) curtailment and mitigation of space debris generation for the near term, and (2) long-term debris mitigation.
Applicability	The IADC guidelines apply to mission planning and the design and operation of spacecraft and orbital stages. Existing spacecraft/orbital operators are encouraged to apply it.	The UNCOPUOS guidelines apply to "mission planning and the operation of newly designed spacecraft and orbital stages" and "if possible to existing ones." The UNCOPUOS guidelines are not legally binding on nation-states.
Terms and definitions	The IADC provides definitions of terms for the reader's convenience. The IADC defines "space debris" as "all manmade objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional."	The UNCOPUOS guidelines do not adopt or transfer the IADC definitions and aeronautical formulations, or generally define terms. The UNCOPUOS guidelines, in the "Background" and only "[f]or the purpose of this document," restate the IADC definition of "space debris."
Mitigation plan	IADC guidelines identify six specific and essential elements necessary in a mitigation plan.	The UNCOPUOS guidelines do not adopt the IADC mitigation plan outline per se. However, they endorse a revision of the seven IADC guidelines for consideration in space mission planning, design, manufacture, and operations.

[a] Inter-Agency Space Debris Coordination Committee, *Space Debris Mitigation Guidelines*, IADC-02-01, revision 1, September 2007, available at http://www.iadc-online.org/index.cgi?item=docs_pub.

[b] United Nations Office for Outer Space Affairs, *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space,* United Nations, New York, N.Y., 2010, available at http://orbitaldebris.jsc.nasa.gov/library/Space%20Debris%20Mitigation%20Guidelines_COPUOS.pdf.

A central feature in the making of the IADC and UNCOPUOS guidelines is that the process avoided the more political, but more authoritative, process of law making.[16] In pragmatic terms, this resulted in affirmative progress because consensus was established and guidance defined that would have been less likely in a formal law-making process. Because the success of a treaty-making process was dubious, the existence of the less formal, nonbinding IADC and UNCOPUOS guidelines is a positive development. However, there is an equally pragmatic and yet to be determined development: the success of the IADC and UNCOPUOS guidelines going forward. In the near and medium term, it is not possible to depend on the force of law for their further development and enforcement, and for compliance.

- ROSCOSMOS (Russian Federal Space Agency)
- UKSpace (United Kingdom Space Agency).

[16] For purposes of this study the terms "law making" and "treaty making" are the same.

The IADC and UNCOPUOS guidelines' success will depend on the ongoing ability of the IADC to withstand the inevitable political forces that will arise over time; the reasonable assumption that the participating entities intend to keep their agreements; and the political will of both the IADC members and the international community. Compliance will be a matter of peer pressure and political will. This can be a delicate balance to strike. The importance of good political will is demonstrated by the fact that the IADC sought to interact with the UNCOPUOS STSC and the UNGA.

That an alternative to a law-making process was intended is evident in three strategies that were used to establish the guidelines: first, only space-faring nations were organized to promote them; second, a forum with the competency to address only scientific and technical issues rather than legal issues was employed; and third, entities, in this case space agencies, were used that did not have the authority to legally bind their nations. The first two of these each has the potential to generate a corresponding negative political force that could inhibit further development and application of, or compliance with, the IADC and UNCOPUOS guidelines. These can include, for example, bloc votes by nonspacefaring nations and attempts in the UNCOPUOS Legal Subcommittee of Committee on the Peaceful Purposes of Space (LSC) to assert its competency regarding orbital debris issues.

The Czech Republic submitted a working paper regarding debris guidelines at the March 2011 session of the LSC.[17] It contains a proposal that the LSC turn the UNCOPUOS guidelines into a set of principles that, the working paper further proposes, will also be presented to the UNGA for adoption. The existing declarations of principles address the exploration and use of outer space;[18] direct television broadcasting;[19] remote sensing;[20] nuclear power sources;[21] and, international cooperation.[22] A major rationale for proposing that a set of orbital debris principles be formulated is that the UNCOPUOS guidelines "are generally conceived as a list of specific measures 'that curtail the generation of potentially harmful space debris in the near term' and 'that limit their generation over the longer term' [but] [t]he guidelines do not mention the protection of the environment as one of their aims."[23]

The working paper is the first step toward formally placing the subject of orbital debris principles on the LSC agenda. If the subject is placed on the agenda, the next step is to begin deliberations to formulate the guidelines as a statement of principles. If the LSC agrees on a set of principles, the document is sent to UNCOPUOS for adoption and referral to the General Assembly for further acceptance. When the working paper was introduced, nine nations supported it.[24] As of this writing, the United States has not taken a position on the paper. Two major

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[17] United Nations Committee on the Peaceful Uses of Outer Space, "Review of the Legal Aspects of the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, with a View to Transforming the Guidelines into a Set of Principles To Be Adopted by the General Assembly, Working Paper Submitted by the Czech Republic," Document A/AC.105/C.2/L.283, United Nations General Assembly, New York, N.Y., March 9, 2011.

[18] United Nations, "Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space," General Assembly Resolution 1962 (XVIII), United Nations General Assembly Official Records, 18th Session, 1280th Plenary Meeting, U.N. Doc. A/RES/1962(XVIII), United Nations, New York, N.Y., December 13, 1963.

[19] United Nations, "Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting," General Assembly Resolution 37/92, United Nations General Assembly Official Records, 37th Session, 100th Plenary Meeting, U.N. Doc. A/RES/37/92, United Nations, New York, N.Y., December 10, 1982.

[20] United Nations, "Principles Relating to Remote Sensing of the Earth from Outer Space," General Assembly Resolution 47/68, United Nations General Assembly Official Records, 47th Session, 85th Plenary Meeting, U.N. Doc. A/Res/47/68, United Nations, New York, N.Y., December 14, 1992.

[21] United Nations, "Principles Relevant to the Use of Nuclear Power Sources in Outer Space," General Assembly Resolution 47/68, United Nations General Assembly Official Records, 47th Session, 85th Plenary Meeting, U.N. Doc. A/Res/47/68, United Nations, New York, N.Y., December 14, 1992.

[22] United Nations, "Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries," General Assembly Resolution 51/122, United Nations General Assembly Official Records, 51st Session, 83rd Plenary Meeting, U.N. Doc. A/Res/51/122, United Nations, New York, N.Y., December 13, 1996.

[23] United Nations Committee on the Peaceful Uses of Outer Space, "Review of the Legal Aspects of the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, with a View to Transforming the Guidelines into a Set of Principles To Be Adopted by the General Assembly, Working Paper Submitted by the Czech Republic," March 9, 2011, p. 2.

[24] The nations are Belgium, Brazil, China, Germany, Italy, Morocco, the Netherlands, Portugal, and Saudi Arabia. Belgium expressed the view that a fault standard ought to be applied. China reserved the right to make additional comments under a different agenda item (J.I. Gabrynowicz, "Unpublished notes re: UNCOPUOS LSC AM Session," 2011).

spacefarers, France and Russia, expressed doubts about the utility of creating a set of principles at this stage.[25] The LSC is fundamentally a political body; therefore, if the subject is placed on the agenda and if deliberations and debate begin, then anything is possible.

The IADC and UNCOPUOS guidelines process is representative of an existing and growing trend in which voluntary intergovernmental organizations attempt to generate agreements that may be categorized as "soft law"[26] but whose actual status is far from clear.[27] These include, for example, the Group on Earth Observations, the Committee on Earth Observations Satellites (CEOS), and the International Charter—Space and Major Disasters, as well as the IADC.[28] This "soft law" approach may, in the indeterminate long term, influence the behavior of nations that in turn could become legally binding custom.

> **Finding: The institutions and agreements that have been used to address issues related to orbital debris are primarily political, not legal, in nature. The success of those agreements will thus depend on a complex interplay of good faith; political will; and political, economic, and, sometimes, legal forces.**
>
> **Recommendation: NASA should continue to engage the international community in efforts to develop cooperation and political will regarding activities concerning orbital debris.**

Cooperation with the Private Sector

The issue of cooperation is appropriately addressed with commercial and civil space organizations, as well as the private sector. Until very recently, the U.S. government provided NASA support only for collision avoidance in Earth orbit. Some members of the committee have personally observed some operators incorrectly assuming that the government was screening for potential threats and would notify them if such an occasion arose and would then direct them to take specific remedial action. In fact, the only screening being done was for DOD and NASA satellites, despite national dependence on commercial satellites for the majority of communications supporting operations in Iraq and Afghanistan.

Combined with the assumption that the government screened for potential threats, many operators also assumed that, despite the large number of objects in orbit, space itself was so large that the chances of collision were small.[29] That assumption changed somewhat following the Chinese anti-satellite missile test. Iridium briefly worked with the JSpOC in an attempt to screen Iridium satellites. However, the process proved to be so onerous and the data so poor that Iridium ceased the effort.

Although about the same time, a number of GEO operators were realizing that they were not receiving sufficient quality data for their spacecraft in order to make decisions about maneuvers to avoid collisions in increasingly crowded orbits. Therefore in 2009 Intelsat, SES, and Inmarsat formed the not-for-profit Space Data Association[30] to provide a legal foundation for prototype efforts. By then, a large number of GEO operators were convinced of the utility of self-managing the crowded orbit problem to protect their investments and avoid unnecessary or overly strict future government regulation that they believed might impose undesirable requirements. In addition, many LEO operators, frustrated by the U.S. government's limited capabilities, also expressed interest.

Since that time, the U.S. Strategic Command (USSTRATCOM) has shown a heightened interest in providing these services. USSTRATCOM provides a subset of its Special Perturbations (SP) data to commercial satellite

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[25] K. Hodgkins, U.S. Department of State, e-mail response to inquiry by Committee for the Assessment of NASA's Orbital Debris Programs, April 9, 2011, National Research Council, Washington, D.C.

[26] "Soft law," and what it comprises, is an important and developing legal trend. However, there is no relevant or conclusive consensus or authority that currently exists or will exist in the time frame being addressed by this study.

[27] M. Ferranzani, Alternative approaches to international space cooperation, *ESA Bulletin,* No. 110, pp. 76-80, May 2002, available at http://www.esa.int/esapub/bulletin/bullet110/chapter10_bul110.pdf.

[28] Ferranzani, *ESA Bulletin,* 2002.

[29] J. Campbell, K. Hackmeier, K. Hodgkins, G. Jansson, T.S. Kelso, and R. Reese, "Forum on National Security Space: Examining Codes and Rules for Space," Washington Roundtable on Science and Public Policy, George C. Marshall Institute, Washington, D.C., June 7, 2007.

[30] Space Data Association website, available at http://www.space-data.org/sda/.

operators. Some operators appear to accept that the USG provides adequate service and possesses adequate knowledge. Reasons for this acceptance are, perhaps, that such operators are not convinced that they could do as well as the U.S. government and because they believe that using the service removes some of the legal liability from a future collision. However, the U.S. government requires operators to accept a legal agreement that absolves the government of any responsibility in such an event.[31]

> **Recommendation: NASA should assess the value of alternative data sets, such as by participating in the not-for-profit Space Data Association, to determine how sharing operator ephemerides might improve the accuracy and efficiency of NASA's Conjunction Assessment Risk Analysis (CARA) by incorporating the best data possible in its CARA process.**

INTERNATIONAL COOPERATION AND COOPERATION WITH THE COMMERCIAL SPACE INDUSTRY

The space law treaty regime consists of five international treaties, four of which are widely accepted and one of which is less accepted.[32] The parts of this regime that are most relevant to orbital debris issues are Article IX of the Outer Space Treaty (see Box 11.1) and the Liability Convention. The degree to which these provisions would apply to any given situation is highly fact-dependent and could vary widely from situation to situation.

The space law treaty regime is unquestionably applicable to what has been characterized as "active debris removal (ADR)."[33] The 2010 National Space Policy provides that ". . . the United States shall . . . [p]ursue research and development of technologies and techniques, through . . . [NASA] . . . and the Secretary of Defense, to mitigate and remove on-orbit debris . . . ."[34] This language limits debris removal activities to "research and development." However, NASA's Orbital Debris Program Office has reported that the "key to stabilize the future LEO environment [is] . . . an active debris removal of about five objects per year starting in the near future (~2020) . . ."[35] It further reports that the "[o]nly remediation of the near-Earth environment [is] the removal of existing large objects from orbit" and that "[o]wnership, legal liability, policy, etc." present a "challenge."[36] This is a forward-leaning stance that indicates an aspiration to go beyond the National Space Policy guidance when possible. It also acknowledges the challenging legal and liability aspects of active debris removal.

To the degree that any debris removal activity involves identifying, selecting, and removing any given object—

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[31] "The User agrees to hold harmless the U.S. Government, any agencies and instrumentalities thereof, and any individuals, firms, corporations, and other persons acting for the United States. Such shall be immune from any suit in any court for any cause of action arising from the provision or receipt of space situational awareness services or information, whether or not provided in accordance with 10 USC 2274, or any related action or omission. See, 10 USC 2274 (g)," Space Track, "User Agreement," Space Track, August 25, 2010, available at https://www.space-track.org/perl/user_agreement.pl, accessed July 5, 2011.

[32] The space law treaty regime consists of five international treaties; the first four are widely accepted, the fifth is less accepted. They are:

1. The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, *opened for signature* Jan. 27, 1967, 18 U.S.T. 2410, 610 U.N.T.S. 205;
2. Convention on International Liability for Damage Caused by Space Objects, *opened for signature* Mar. 29 1972, 24 U.S.T. 2389, 961 U.N.T.S. 187;
3. Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, *opened for signature* Apr. 22, 1968, 19 U.S.T. 7570, 672 U.N.T.S. 119;
4. Convention on Registration of Objects Launched into Outer Space, *opened for signature* Nov. 12, 1974, 28 U.S.T. 695, 1023 U.N.T.S. 15; and
5. Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, *opened for signature* Dec. 18, 1979, 1363 U.N.T.S. 21.

[33] C. Bergin, "Project ADR: Removal of Large Orbital Debris Interests NASA—Study," NASASpaceFlight.com, January 9, 2011, available at http://www.nasaspaceflight.com/2011/01/project-adr-removal-large-orbital-debris-nasa-study/, accessed July 5, 2011.

[34] *National Space Policy of the United States of America*, June 28, 2010, p. 7, available at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf, accessed July 6, 2011.

[35] J.-C. Liou, "NASA's Long-term Debris Environment and Active Debris Removal Modeling Activities," presentation at the International Conference on Orbital Debris Removal, Chantilly, Va., Orbital Debris Program Office, NASA Johnson Space Center, Houston, Tex., December 2009, available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100000157_2009042964.pdf, accessed July 5, 2011.

[36] Liou, "NASA's Long-term Debris Environment and Active Debris Removal Modeling Activities," 2009.

BOX 11.1
Article IX of the United Nations Outer Space Treaty (1967)

Article IX of the UNOST of 1967 is as follows:

> In the exploration and use of outer space, including the Moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of co-operation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty. States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose. If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the Moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment. A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party in outer space, including the Moon and other celestial bodies, would cause potentially harmful interference with activities in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, may request consultation concerning the activity or experiment.[1]

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[1] See http://www.oosa.unvienna.org/oosa/SpaceLaw/outerspt.html.

debris or otherwise—from space, actual removal requires crossing a crucial national and international legal threshold. It is a clear international legal principle that no nation may salvage, or otherwise collect, the space objects of other nations that are in space.[37] This fact is particularly critical when one considers that only about 30 percent of the objects cataloged by the Space Surveillance Network are attributed to the United States.[38] No state has the legal authority to remove a debris object from space without the express consent of the object's state of registry. In the United States, obtaining that consent would involve formal diplomacy and the U.S. State Department. A bilateral or multilateral agreement to retrieve debris would require a technical exchange of data and information about an object's design that could involve national security, foreign policy, the International Traffic in Arms Regulations (ITAR), contractual rights, intellectual property rights, and other interests. "Space salvage and removal operations in space will cause international friction, if they are undertaken in the absence of international consensus . . . ."[39] Absent formal diplomatic engagement with other nations, the United States would be limited to retrieving only objects on its own registry.

Finally, and most significantly, no accepted legal definition of "debris" exists. The term does not exist in any of the treaties. The Liability Convention defines "space object" as follows: "[t]he term 'space object' includes component parts of a space object as well as its launch vehicle and parts thereof."[40] "However, it is unclear from the legal documents, [and] related writings . . . whether 'space object' includes space refuse."[41] Science and

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[37] N. Jasentuliyana, Regulation of space salvage operations: Possibilities for the future, *Journal of Space Law* 22(5):5, 1994, available at http:// www.spacelaw.olemiss.edu/jsl/pdfs/back-issues/jsl-22-1.pdf.

[38] J.-C. Liou, ed., Satellite box score, *Orbital Debris Quarterly News* 15(3):10, 2011.

[39] R.C. Hall, Comments on salvage and removal of man-made objects from outer space, *Journal of Air Law and Commerce* 33(288):3, 1967.

[40] Liability Convention Art. 1 (d).

[41] H.A. Baker, *Space Debris: Legal and Policy Implications,* Utrecht Studies in Air and Space Law, Volume 6, Martinus Nijhoff Publishers,

engineering can contribute greatly to crafting an acceptable and practical definition of "debris"; it can address important practical questions regarding an object's design, threat potential, functionality or lack thereof, and so on. In the final analysis, however, each object placed in space is legally analogous to a piece of sovereign territory on Earth. As such, they are matters of intense sovereign interest. The question of whether or not a particular object is to be removed from space as "debris" will be scrutinized through a strong filter of national interests and security. The legal principle that forbids one nation from taking the space object of another has deep roots: it goes back to the early days of the Cold War era when the USSR and the United States wanted to deny each other a facile excuse to seize one another's satellites in order to engage in reverse engineering. The Cold War is over, but the acute sensitivity regarding satellite technology remains. It is not in the U.S. national interest to use a less-than-formal process to reach agreements with other nations regarding debris removal. Absent a formal, transparent, officially acknowledged process, active debris removal could be easily perceived as illegal interference with the space objects of other nations.

Even if the United States were to retrieve only its own objects, another kind of legal threshold would have to be crossed at the national level. Formal congressional involvement in debris removal activities would be catalyzed because they precipitate potential U.S. responsibility and liability for those activities at international law.[42] It would also trigger the necessity of determining which objects the government appropriately removes and which are appropriately removed by a private entity.[43] "The development of this new technology may require both governments and the private sector working together."[44] Congress will also have to address a debris removal risk-sharing regime between and among the government and private actors. The risk-sharing liability and cap system that has been part of U.S. national launch law since 1984[45] could provide a model for retrieval activities. In three different instances of removal of an object from space, that is, an Intelsat satellite, the *Palapa,* and a Westar satellite, the government required agreements in which it was to be held harmless in the event of an accident.[46] Whether this practice is desirable or sustainable for the long term will have to be addressed.

Finally, even if the United States were to retrieve only its own objects, it is still in the U.S. national interest to use a formal process to inform appropriate space actors about U.S. actions through a formal, officially acknowledged, confidence-building process regarding its national actions. This is necessary to avoid perceptions of the United States taking unilateral actions that may be a cover for nonpeaceful purposes or illegal actions.

Finding: Debris removal activity that involves selecting and removing any given object—debris or otherwise—from space, crosses crucial national and international legal thresholds.

Recommendation: NASA's meteoroid and orbital debris programs should engage the NASA General Counsel's Office and, through that office, the U.S. State Department regarding the legal requirements and diplomatic aspects of active debris removal.

Dordrecht, The Netherlands, 1989, p. 132.

[42] The Outer Space Treaty, Art. VI: "States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty. When activities are carried on in outer space, including the Moon and other celestial bodies, by an international organization, responsibility for compliance with this Treaty shall be borne both by the international organization and by the States Parties to the Treaty participating in such organization."

[43] "All objects which pose a threat to safety in space flight should be subject to governmental capture and removal under international regulations. However, errant satellites, representing substantial residual value, and not threatening the orbital paths or trajectories of functioning ones, should be a private, not a public responsibility." See H. DeSaussure, The application of maritime salvage to the law of outer space, p. 131 in *Proceedings of the 28th Colloquium on the Law of Outer Space,* 1986, American Institute of Aeronautics and Astronautics, New York, N.Y.

[44] J.-C. Liou and N. L. Johnson, Risks in Space from orbiting debris, *Science* 311(5759):340-341, 2006.

[45] 49 U.S.C. Sec. 70101 et. seq.

[46] C. Kunstadter, XL Insurance, verbal response to inquiry by the Committee for the Assessment of NASA's Orbital Debris Programs at the Workshop to Identify Gaps and Possible Directions for NASA's Micrometeoroid and Orbital Debris Programs on March 9, 2011, National Research Council, Washington, D.C.

12

Management and Organizational Issues

NASA meteoroid and orbital debris (MMOD) programs are budgeted and operated through an organizational structure in which there is no single management and coordination point. This mode of operation is partly the result of growth in the MMOD programs from different organizations within the NASA structure. Key decisions pertaining to MMOD safety, including whether to maneuver a craft in response to a possible collision with debris, are made mostly at the mission level, essentially leaving the debris problem to the heads of the various mission operators. Formally, this is a highly decentralized decision system. Communication among program managers and senior debris scientists appears to be effective but is not facilitated by a decision system with a central coordination point. In addition, some members of the committee have personally observed that inter-agency cooperation, information sharing, and coordination can be hampered by what are often referred to as "security issues," whether real or perceived. This lack of cooperation and coordination could have negative consequences if errors are made either by NASA personnel or by the users of NASA's hazard assessment or debris mitigation models. Of particular note is what often appears to be the Department of Defense's (DOD's) unwillingness to provide raw debris tracking data to NASA personnel involved in performing COLA/CARA calculations.[1]

As the NASA orbital debris programs have grown, so also have the number of organizations that they support or depend on to obtain essential data, both national and international. This interdependency has created complex reporting lines as well as a need for integrated policy decisions. In addition, funding sources have often been fragmented, centered on individual program needs of the space agency.

Recent efforts[2] to bring funding authority and personnel reporting lines under a single office at NASA headquarters seem appropriate. If this approach succeeds, efforts to solve present and future orbital debris problems may be less fragmented and accomplished through more stable and consistent levels of resource allocation. This type of structure would also facilitate the evaluation of cost-effectiveness and safe approaches to the removal of orbital debris from low Earth orbit (and geosynchronous Earth orbit, if necessary) and would allow the monitoring of adherence to mitigation guidelines as well as the need to modify or expand any current mitigation practices. The end result would be programs better able to execute their missions and better able to maintain, and even enhance, the internationally recognized leadership position of NASA. A central coordination point would also facilitate the

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[1] L. Newman, "NASA Robotic Conjunction Assessment Risk Analysis (CARA): Process and System Overview," presentation to the Committee for the Assessment of NASA's Orbital Debris Programs, December 14, 2010, National Research Council, Washington, D.C.

[2] J.W. Lyver, NASA, "Proposal for Establishing a NASA Umbrella Program for Space Debris in FY-2012," presentation dated May 13, 2010, Office of Safety and Mission Assurance, Safety and Assurance Requirements Division, NASA, Washington, D.C.

development of an effective and implementable strategic plan (see below) and need not be a single administrative position (for example, it could be a steering committee of senior program managers).

> **Finding: NASA's management structure has not kept pace with the expanding responsibilities of its MMOD programs. Consequently, the MMOD programs do not have a single management and budget point that can efficiently coordinate all of the current and planned activities and establish clear priorities.**
>
> **Recommendation: NASA should review the current management structure of its MMOD programs in order to achieve better coordination, provide improved central decision making, and establish a framework for setting priorities. This framework should include a major interface with Congress, other federal and state agencies, and the public.**

AN EXPANDING RESPONSIBILITY

The 2010 National Space Policy expands NASA's role in MMOD risk assessment to include the potential removal of debris from space, although NASA may not be the party to actually do this. NASA's MMOD programs have as yet conducted only preliminary assessments of the issues associated with the return of debris to Earth. As discussed elsewhere in this report, these early assessments suggest that active removal of as few as five large objects a year may have a significant impact on controlling the future growth of debris generated by collisional events.[3] Detailed analysis will be needed to assess the costs, benefits, and risks associated with alternative actions for debris removal.

The nature of NASA'S meteoroid and orbital debris efforts are continuous and long term in nature, whereas programmatic funding becomes available on an annual basis and is subject to unpredictability. Implementation of the 2010 National Space Policy will necessarily increase the demands placed on NASA's MMOD programs. Funding levels to support orbital debris programs have been flat or shrinking in real dollars, while responsibilities and programs have been growing. As a result, optical sampling of the space environment has been reduced, analysis of the Haystack data has been limited, tests that would provide more accurate breakup models have not been conducted, needed support for operational missions has sometimes not been available, and model updates/releases have been delayed.

OUTREACH AND PEER REVIEW

During its review of NASA's MMOD efforts, the committee noted several instances of research results not being conveyed or communicated to the community at large. Some groups and individuals within NASA do publish their work through a rigorous peer review process; for example, the record of peer-reviewed publications for the LEGEND work is commendable. Other groups and individuals do not pursue peer-reviewed publication, or appear to misconstrue what is meant by peer review, perhaps because of a perceived lack of incentive or reward for following a rigorous publication process. As an example, the committee notes that only approximately 25 percent of the references cited as being instrumental to the development of the ORDEM2000 environment model were peer-reviewed prior to its launch; the remaining references were either other NASA publications or internal NASA documents or communications that are unavailable or difficult to access by those outside NASA.

The concerns with not bringing forth work for peer review in a timely manner are two-fold:

1. The space community is not apprised of NASA's work and results, nor is it made privy to NASA's thought process behind rules, regulations, or policies that it develops or supports.
2. The inference can be drawn that if the work is not published through a rigorous peer-review process, it may not be technically sound.

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[3] These early assessments have a number of assumptions behind this conclusion. See Chapter 1.

Peer review of research may not be appropriate in all situations; for instance, conferences and workshops may be better suited for presentation of some types of research. However, peer review does represent an effective method of conveying scientifically tested and accepted results, underlying intricacies, and other key pieces of information to the community at large.

Finding: NASA's MMOD researchers do not consistently communicate the results of their work to the scientific community, with the result that users of NASA's codes and models have less understanding regarding the underlying assumptions and intricacies in each code and model.

Recommendation: NASA should encourage its MMOD researchers to more fully communicate the results of their work and their development activities, such as in appropriate peer-reviewed publications when possible, so that users of NASA's codes and models gain a greater appreciation for and more clearly understand the underlying assumptions and intricacies in each code and model.

LACK OF DEPTH IN STAFFING

Because of the steadily increasing number of ventures in space, the expertise of NASA's MMOD programs is increasingly sought after by a wide variety of space exploration parties. As pointed out in Chapter 1, "Introduction and Historical Background," the resources provided to NASA's programs (funding, personnel, research support, and so on) have not, however, been increased to meet these growing demands. In fact, many of the operations within NASA that are related to orbital debris are "one civil servant deep" and include a support staff of mostly on- and off-site contractors. As such, there is no redundancy within NASA in case of retirements or resignations. This shallowness of personnel coverage could seriously jeopardize a number of ongoing life- and mission-critical operations should a program or activity lead retire, resign, or be re-assigned.

Finding: Nearly all of NASA's MMOD programs are only one person deep in staffing. This shortage of staffing makes the programs highly vulnerable to budget reductions or changes in personnel. Further reductions in real budgetary support over the coming years could threaten the viability and scope of ongoing MMOD programs.

STRATEGIC PLAN

In December 1981, NASA formulated a draft 10-Year Space Debris Assessment Plan that outlined MMOD goals and planned program developments for 1981 through 1991. This was a valuable document that identified MMOD goals and proposed program developments. The committee has been unable to find, however, any formal MMOD strategic plan covering the period since 1991 to guide MMOD research priorities, budget allocations, and program developments. The committee did examine a 1995 PowerPoint presentation in which one slide stated five general program goals, but no supporting plan was provided. NASA appears to lack a strategic plan for MMOD-related activities, including research, model development, operations, and management, but such a strategic plan is usually a centerpiece of major governmental and corporate programs. MMOD program managers informed the committee that many of the pieces and insights needed for such a plan exist but simply have not been brought together. The lack of such a formal plan, however, encourages making key budget decisions and research priorities in an uncoordinated way, rather than through a coherent, well-thought-out strategy. If such a plan were in place, then, whether funding increased or decreased over time, the plan would provide guidance as to how efforts would be structured and resources allocated.

In the committee's view, a useful strategic plan would address four major questions:

1. *Where are we?* This first step is extremely important because it has to reflect the proper taxonomy of the missions of the organization so that the ensuing efforts are most useful. Overarching Figure 1.1 in Chapter 1 portrays several functions (testing and measurements; model development and use; and services to NASA program

offices, U.S. policy organizations, and international entities) in three mission areas (protect the spacecraft, protect the space environment, and protect people on Earth).

While the NASA MMOD programs are truly high-end service support units, the models that are maintained and applied provide a uniquely value-based perspective as to the importance of the programs, and so the evolution of the key models (e.g., SBM, ORDEM, LEGEND, BUMPER, ORSAT, DAS, and others) would be of significant relevance in a strategic plan. While this may not be the exact framework the NASA MMOD programs would want to follow, it has a level of resolution sufficient to make a strategic plan meaningful.

2. *Where do we want to go?* Goals in each of the areas need to be examined explicitly and concrete metrics for success developed, along with associated timelines.

3. *How are we going to get there?* (This question includes funding.) The NASA MMOD programs have benefited from and contributed to multi-agency and multi-national activities over the years, and so an explanation of how to leverage associated activities should be included. Given this report's highlighting of several areas where expanded efforts would be warranted (see Box 12.1) the funding required to meet the goals laid out in Step 2 should be detailed with clear priorities identified in case full funding cannot be provided by NASA.

4. *How do we measure how we are doing?* It is critical to provide within the strategic plan a means to determine the organization's progress in achieving the objectives of the strategic plan. While the resources to support the MMOD programs have not grown commensurate with the scope and severity of the meteoroid and debris hazard, an ongoing assessment process should be developed that permits NASA to gauge NASA MMOD programs' capability not only to meet the original strategic plan's goals but also to respond dynamically to the ever-changing space environment, by having progress tied to environmental and operational needs. This feature is critical to a strategic plan that is supposed to create operationally viable support services for addressing an environmental issue that continues to evolve and grow.

Although a solid strategic plan provides a great roadmap of what an organization plans to accomplish over a reasonable period of time (probably in the 5- to 10-year timeframe), it should also focus on how these activities will be completed. The strategic plan needs to address the establishment of consistent means to communicate technical findings, uncertainty analyses, and operational consequences regarding the MMOD environment. Noting budget realities within the plan might help focus its priorities. Regular cooperative and collaborative gatherings should be part of the strategic plan's execution, to provide opportunities both for NASA MMOD work to be regularly communicated to the aerospace community and for the research and model development to be peer reviewed and validated. In the past, NASA administrative policies have curtailed this aspect of its MMOD activities, to the detriment of the MMOD programs. The reality that the NASA MMOD programs contribute uniquely to the national and international aerospace community should be reflected in an appropriate emphasis on the programs, an emphasis that includes an allocation of resources from the NASA administration sufficient to ensure regular and substantive communication, cooperation, and collaboration in MMOD-related activities.

> **Recommendation: NASA should develop a formal strategic plan that provides the basis for prioritizing the allocation of funds and effort over various MMOD program needs. Among the potential research needs and management issues to be considered is the selection listed in Box 12.1. The strategic plan should consider short- and long-term objectives, a schedule of benchmark achievements to be accomplished, and priorities among them. Stakeholders should be engaged to help develop and review this plan. Finally, the MMOD strategic plan should be revised and updated at regular intervals.**

BOX 12.1
Research Needs and Management Issues to Be Considered in the Formulation of an MMOD Strategic Plan

Throughout this report, the committee identifies various areas of potential research and a number of management actions that would strengthen NASA's meteoroid and orbital debris (MMOD) programs. Adoption of a strategic plan of the sort envisioned by the committee would require evaluation and prioritization of these areas and activities, which include the following:

1. Perform radar cross-section calibrations using fragments from a large range of materials used in modern satellites and rocket bodies, as well as non-fragmentation debris. (Chapter 2)
2. Expand the environment measurement program to include use of in situ sensors to monitor the flux of debris smaller than a few millimeters. (Chapter 2)
3. Expand efforts to more accurately model sources of debris. (Chapter 3)
4. Develop criteria or a schedule for the regular release of updates to NASA's orbital debris- and meteoroid-related models. (Chapter 3)
5. Establish a base effort to evaluate major environmental uncertainties in three areas: (a) meteoroid velocity distributions, (b) flux of meteoroids of larger sizes (greater than 100 microns), and (c) impact plasma effects. (Chapter 4)
6. Adopt a single model of the meteoroid environment for official use. (Chapter 4)
7. Pursue improving the understanding of the hazards posed by interplanetary meteoroids. (Chapter 4)
8. Expand research on meteoroids to include an understanding of the possible link between spacecraft electrical anomalies and major meteor showers. (Chapter 4)
9. Perform a broad integrative analysis of the various risks posed by meteoroids and orbital debris (whether probabilistic risk analysis or some alternative). (Chapter 5)
10. Identify major areas of uncertainty in current environmental models and risk assessments, and develop test plans and analyses to reduce that uncertainty. (Chapter 5)
11. Undertake an effort to refine models for predicting impact damage using a statistics-based approach. (Chapter 6)
12. Undertake an effort to re-derive the ballistic limit equations in the BUMPER code using a statistics-based approach that would provide information regarding uncertainty bounds and/or confidence intervals. (Chapter 6)
13. Increase efforts to characterize the damage resulting from impacts of orbital debris of various particle shapes and densities. (Chapter 6)
14. Expand program plans to include the technology, political, and legal considerations necessary to increase international cooperation on mitigation and remediation measures to stabilize the orbital debris environment. (Chapter 7)
15. In regard to reentry risks, re-examine how thresholds for ground injury effects are estimated and provide confidence bounds and uncertainty assessments. (Chapter 8)
16. Develop a research plan for (a) assessing the impact of the inaccuracy in the uncertainty in computing the probability of collision and in the ensuing risk assessment and (b) improving the accuracy of the computation of the probability of collision in the presence of these uncertainty errors. (Chapter 9)
17. Initiate an effort to record, analyze, report, and share data on satellite anomalies in order to better quantify the risk from orbital debris particulates too small to be cataloged yet large enough to disrupt space operations. (Chapter 10)
18. Continue to engage the private sector, U.S. federal agencies, and international agencies in developing cooperation and political will to effectively address issues regarding orbital debris. (Chapter 11)
19. Identify budget requirements and areas of responsibilities, including personnel and a single point of contact, for maintaining a viable program as budgets and personnel change. (Chapter 12)
20. Schedule periodic technical assessments written for policy makers and stakeholders. (Chapter 12)
21. Continue to emphasize the long-term objectives of the MMOD programs through public discussions and improved long-term models. (Chapter 13)
22. Monitor and inventory the costs of debris avoidance, mitigation, surveillance, and reporting over time. (Chapter 13)

13

Preparing for the Future

Addressing the problem of orbital debris requires taking a long-term view, but such a view can be difficult for federal agencies that must operate subject to the variability of annual budgets. Even if the present orbital debris population is manageable over the next few years, the longer-term problem of growth in orbital debris from self-propagation alone, coupled with wholly new additions to the debris population, remains a concern. In this way, the problem of space debris is similar to a host of other environmental problems and public concerns characterized by possibly significant differences between the short- and long-run damage accruing to society, such as damage related to atmospheric concentrations of greenhouse gases, storage of nuclear waste, and long-lived pharmaceutical residue in underground aquifers. Each has small short-run effects but, if left unaddressed, will have much larger impacts on society in the future.

THE CHALLENGE OF LONG-LIVED PROBLEMS

Because long-term problems can seem unimportant today even if they will loom large in the future, they are often easily deferred or outright ignored. Future consequences are difficult to express as consequences of concern today, in terms of both the quantitative estimation of future physical damage, and quantification of damage into economic or other tangible harm, and the discounting procedures that translate the costs of future harmful effects into today's dollars.

These concerns led the committee to characterize the problem of managing space debris as both a challenge and an opportunity to preserve the space environment for future generations.[1] A critical aspect of this problem is asking and answering the question: What is the damage from orbital debris not only today but also tomorrow? Understanding the consequences of orbital debris requires a long-term perspective. Another important element that is also missing is the measurement of the orbital debris problem in economic terms.

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[1] Simpson, J.A., Preservation of Near-Earth Space for Future Generations, Cambridge University Press, Cambridge, MA, 1994; Baiocchi, D. and W. Welser, IV, Confronting Space Debris: Strategies and Warnings from Comparable Examples Including Deepwater Horizon, RAND Corporation, Santa Monica, CA, 2011, available at http://www.rand.org/pubs/monographs/MG1042.html, accessed July 5, 2011; Macauley, M.K., "In Pursuit of a Sustainable Space Environment: Economic Issues in Regulating Space Debris," Chapter 18 in Preservation of Near-Earth Space for Future Generations, John A. Simpson, ed., Cambridge University Press, Cambridge, MA, 1994, p. 147-158.

THE FINANCIAL IMPACT OF ORBITAL DEBRIS

The cost of orbital debris can be measured in different ways. For example, spacecraft replacement cost is one measure of the economic harm caused by a catastrophic debris impact.[2] This measure assumes that a spacecraft can be readily replaced, but replacement may be difficult because of lack of funding, launch window limitations, or other constraints. In addition, replacement cost alone underestimates the full cost to society of debris impact, because the debris generated by an impact has the potential to harm other spacecraft, thus posing additional costs for society beyond those incurred simply in spacecraft replacement.

The costs of orbital debris also take other forms. Shielding, debris avoidance maneuvers, and other efforts to avoid debris impact increase the cost of spacecraft design and operation. Similarly, actions taken to avoid generation of debris, such as the use of lanyards, venting of residual fuel, and moving spacecraft into graveyard orbits, also impose design and operating costs that are usually expressed in terms of mass, fuel, and lifetime penalties. Additional costs are borne in the form of debris surveillance, tracking, and reporting. The economic consequences of debris impacting a government-owned or government-operated spacecraft are borne by taxpayers because the government "self insures" its activities. These consequences take myriad forms: degradation of the services provided by debris-impacted spacecraft or loss of a mission altogether. The costs may not be reported directly and may be contained within the mission agency's budget, but the costs are real nonetheless. Additional costs come in the form of any long-lived debris that may pose future harm to spacecraft, and are not measured at present.

The committee requested but received little information about the effect on space mission budgets of the need to shield, maneuver, move to a graveyard orbit, or take other protection measures against orbital debris. In the information received, one estimate was that 0 to 10 percent of mission cost was required to implement shielding and avoidance maneuvers; in another case, it was 5 to 10 percent of mission cost. Some reported incorporating collision avoidance into regularly scheduled maneuvers. Generally speaking, the information provided to the committee suggested that few experts see addressing orbital debris as imposing a large financial burden at present. Such a conclusion hardly supports the need to worry about debris, making the case seem weak to enhance space debris monitoring, modeling, and data collection or to consider investment in active debris removal. The committee emphasizes, however, that data is lacking on the economic cost of the future orbital debris population. If the cost were expected to be large, the economic case could be stronger for investment in improved debris models, monitoring, and removal.

In the case of commercially owned and operated spacecraft, companies insure their operations against loss of service, including loss of service due to debris impact. At present, insurers report that of the overall insurance premiums for spacecraft, the portion attributable to the possibility of a debris impact is quite small—less than 1 percent. They point out that debris impact is currently seen as a low-probability event.[3] In terms of debris-related harm that might be created for other operating spacecraft if an insured spacecraft is damaged by a debris impact, insurers reported that they assume that the companies owning insured spacecraft operate as "good citizens." In other words, insurers do not take account of whether an insured spacecraft will be a source of debris, and thus a potential harm to others. They insure only against harm to the insured spacecraft.

Going forward, NASA, other space operational agencies, and the commercial space industry could consider keeping better track of debris-related costs. Agencies should combine projections of the future debris population with estimates of potential economic damage. The absence of more transparent cost reporting can lead to underestimation of future debris-related problems. If costs were routinely inventoried and reported, they could provide a benchmark on the economic importance of managing debris. Such a benchmark would demonstrate the value of debris mitigation guidelines and help to inform when to tighten them, if costs were to grow. In addition to the many purposes it could serve, a cost benchmark can also help decision makers to assess the value of possible future investment in active debris removal technology.

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[2] Ailor, W., J. Womack, G. Peterson, and E. Murrell, "Space Debris and the Cost of Space Operations," presented at the 4th International Association for the Advancement of Space Safety Conference, Huntsville, Alabama, May 19-21, 2010.

[3] Kunstadter, C., "Space Insurance and NASA's MMOD Program," presented at the NRC Workshop to Identify Gaps and Possible Directions for NASA's MMOD Programs, Fairfax, VA, March 10, 2011. See also: Swiss Re, *Space Debris: On Collision Course for Insurers?* Swiss Re, Zurich, Switzerland, 2011.

Finding: The long-lived problem of growth in the orbital debris population as a result of debris self-collision and propagation requires that NASA take a long-term perspective to safeguard the space environment for future generations.

Finding: Although the meteoroid and orbital debris environment may be manageable at present, debris avoidance, mitigation, surveillance, tracking, and response all require money. At present, these costs usually come in the form of additional spacecraft mass and fuel and in the maintenance of debris surveillance systems. Such costs are usually absorbed in the budgets for space mission design, operations, and, in the case of commercial activities, insurance premiums. In the absence of appropriate meteoroid and orbital debris management to deal with the issue, these costs may grow over time. Although they can serve to highlight the importance of NASA's debris measurement and monitoring activities, at present these costs are not routinely measured and reported.

Finding: The cost of replacing spacecraft has been used as a measure of the economic harm of a catastrophic debris impact but may underestimate the full cost of harm for two reasons: (1) actual replacement may be difficult because of funding, launch window limitations, or other constraints; and (2) replacement cost, insurance premiums, and other measures of the cost incurred to protect a spacecraft understate the full cost to society as a whole if that spacecraft, damaged by a meteoroid or orbital debris, itself generates debris that then creates potential harm to other spacecraft.

Recommendation: NASA should lead public discussion of the space debris problem to emphasize debris as a long-term concern for society that must continue to be addressed today. Necessary steps include improvements in long-term modeling, better measurements, more regular updates of the debris environment models, and other actions to better characterize the long-term evolution of the debris environment.

Recommendation: NASA should join with other agencies to develop and provide more explicit information about the costs of debris avoidance, mitigation, surveillance, and response. These costs should be inventoried and monitored over time to provide critical information for measuring and monitoring the economic impact of the meteoroid and orbital debris problem, signaling when mitigation guidelines may need revision, and helping to evaluate investments in technology for active debris removal.

14

Compiled List of Findings and Recommendations

This chapter contains all of the findings and recommendations from the various chapters of this report.

CHAPTER 1: INTRODUCTION AND HISTORICAL BACKGROUND

Finding: NASA's meteoroid and orbital debris programs have used their resources responsibly and have played an increasingly essential role in protecting the safety of both crewed and uncrewed space operations.

Finding: The increasing responsibilities given to NASA's meteoroid and orbital debris programs have put pressure on the programs' allotted resources. The increasing scope of work, and the complexity and severity of the debris and meteoroid environment, are outpacing in real dollars the decreasing funding levels of NASA's MMOD programs.

CHAPTER 2: ORBITAL DEBRIS ENVIRONMENT: DETECTION AND MONITORING

Finding: The current lack of radar cross-section calibrations using fragments from a larger range of materials used in modern satellites and rocket bodies, as well as non-fragmentation debris, represents a significant source of uncertainty in interpreting key measurements of the orbital debris environment.

Finding: NASA's orbital debris programs do not include the capability to monitor with in situ instrumentation the penetrating flux of objects smaller than a few millimeters. Data collected by in situ monitoring could be used to resolve uncertainties in measurements made remotely, to help identify new sources of debris, and to provide clues to the causes of spacecraft anomalies.

CHAPTER 3: ORBITAL DEBRIS MODELING AND SIMULATION

Finding: Correctly characterizing the shape and material properties of orbital debris is critical to correlating the results of ground-based satellite impact tests with radar cross-section data and thus to predicting the damage caused by debris particles, yet there has been little effort to include realistic effects

of shape in the standard breakup model. These enhancements would also serve to improve BUMPER's accuracy in predicting risks.

Recommendation: The NASA Orbital Debris Program Office should expand its efforts to more accurately incorporate data on sources of debris into the standard breakup model, especially (1) empirical results from recent major on-orbit collisions, (2) data from laboratory rocket body collision tests (which need to be planned and conducted), (3) results from hypervelocity impact tests with payloads using newer construction methods and materials, and (4) enhanced data on fragment shape characteristics.

Recommendation: NASA's Orbital Debris Program Office should release the next version of the Orbital Debris Environment Model as soon as possible and provide updates on a regular basis or as often as required as a result of major changes to the orbital debris environment or improved characterization of that environment, including characterization of debris shape, as applicable.

CHAPTER 4: THE METEOROID ENVIRONMENT AND ITS EFFECTS ON SPACECRAFT

Finding: The models used to relate measurements of plasma to fundamental parameters of a meteoroid contain large uncertainties and errors. These models include, but are not limited to, electromagnetic scattering models, luminous emission models, and meteoroid fragmentation models.

Finding: Because the scientific community infers the properties of a meteoroid indirectly from its effects on the atmosphere (a meteor) or the effects of its impact on a spacecraft, it is imperative to understand observational biases inherent in each instrument that affect the detection of these secondary effects.

Finding: The Meteoroid Environment Model incorporates in its predictions the latest available data on the meteoroid environment, including the directionality and full velocity distribution of the meteoroids. It is currently the NASA model that is most consistent with the known meteoroid environment, although some major uncertainties still remain.

Recommendation: The NASA meteoroid and orbital debris programs should establish a baseline effort to evaluate major uncertainties in the Meteoroid Environment Model regarding the meteoroid environment in the following areas: (1) meteoroid velocity distributions as a function of mass; (2) flux of meteoroids of larger sizes (>100 microns); (3) effects of plasma during impacts, including impacts of very small but high-velocity particles; and (4) variations in meteoroid bulk density with impact velocity.

Finding: The earlier SSP 30425 meteoroid model does not reproduce existing observational meteoroid data with a fidelity equal to that of the Meteoroid Environment Model. Numerous disparate sources of data have been fused to produce the current meteoroid flux model used by NASA, sometimes incorporating differing underlying assumptions.

Finding: The Meteoroid Environment Model currently does not extend to prediction of the meteoroid environment in the outer solar system, and the measurements it incorporates are poorly constrained in the cis-martian region.

Recommendation: An effort should be made to re-examine earlier data used in the Grün Interplanetary Flux Model and to reconcile the data with more recent measurements in the literature on meteoroid flux, and a technical evaluation should be undertaken to synthesize and document such data as it is incorporated into the Meteoroid Environment Model (MEM). Updates of the MEM and technical development should follow a technical pathway as rigorous as that being taken for updates of the Orbital Debris Environment Model.

Recommendation: NASA should adopt the Meteoroid Environment Model for agency-wide official use and extend its capabilities to the outer solar system.

CHAPTER 5: RISK ASSESSMENT AND UNCERTAINTY

Finding: NASA's MMOD risk assessment processes have evolved beyond focusing primarily on the damage to spacecraft from collisions with debris that are too small to track, to incorporating a more complete range of risks. More remains to be accomplished, however, including the need in some cases for more measurements as parameters for risk analyses. As gaps are filled, NASA's MMOD efforts can progress toward ever more integrative risk assessment in which all sources and types of risk are modeled and assessed.

Recommendation: Although NASA should continue to allocate priority attention and resources to collision risks and conjunction analysis, it should also work toward a broad integrative risk analysis to obtain a probabilistic risk assessment of the overall risks present in the MMOD domain in which all sources of risk can be put in context.

Finding: The calculation and communication of information about uncertainty are critical to properly assessing operational alternatives based on calculated risks posed by orbital debris.

Recommendation: NASA's meteoroid and orbital debris programs should increase their efforts to reduce the uncertainty and variability in models through acquisition of measurements (and where necessary, to do testing and analysis) for continually improving assessment of risk and characterization of uncertainty. Together with its MMOD efforts, NASA should continue to advance the agency's efforts to present information on uncertainty in risk analyses. Special attention should be given to maximizing public understanding of uncertainty analysis through peer-reviewed papers and other publications.

CHAPTER 6: SPACECRAFT PROTECTION IN THE MMOD ENVIRONMENT

Finding: The BUMPER program was not designed to fully address the probability of spacecraft failure following penetration by a meteoroid(s) or pieces of orbital debris.

Recommendation: NASA's own MSCSurv code might offer insights for development of an expanded, improved MMOD risk analysis code that fully addresses the risk to a valuable spacecraft following an MMOD impact and, as such, should be coupled with results from BUMPER for use as needed.

Finding: It is not possible to obtain uncertainty bounds and/or confidence intervals as part of the current procedures being used to derive damage predictor equations in BUMPER.

Recommendation: Considering the critical need to develop overall uncertainty bounds for predictions of MMOD impacts (which in turn could be used in a probabilistic risk assessment), NASA should refine its damage prediction models so that they include uncertainty bounds and/or confidence intervals.

Finding: Using aluminum spheres to develop ballistic limit equations for risk assessments for spacecraft may not accurately portray the range of damage likely from impact with an orbital debris particle of any given characteristic size and thus may result in a non-optimum design of the spacecraft's MMOD protection systems.

Recommendation: A priority in the next release of the Orbital Debris Environment Model and Standard Breakup Model should be the inclusion of shape characteristics in the particle distributions to more accurately portray the range of potential damage from an impact with orbital debris.

CHAPTER 7: MITIGATION OF ORBITAL DEBRIS

Finding: NASA's current orbital debris programs are recognized both nationally and internationally as leaders in providing support for defining the environment and related impact hazards associated with orbital debris, and mitigation techniques to effectively minimize the hazards associated with the current and future orbital debris environment.

Finding: Most relevant federal agencies accept all or some of the components of NASA's orbital debris mitigation and prevention guidelines.

Finding: Enhanced mitigation standards or removal of orbital debris are likely to be necessary to limit the growth in the orbital debris population. Although NASA's orbital debris programs have identified the need for orbital debris removal, the necessary economic, technology, testing, political, or legal considerations have not been fully examined, nor has analysis been done to determine when such technology will be required.

CHAPTER 8: HAZARDS POSED BY REENTRY OF ORBITAL DEBRIS

Finding: NASA's Object Reentry Survival Analysis Tool provides results as point estimates without confidence bounds or uncertainty estimates.

Recommendation: In regard to debris reentry risk, NASA should provide confidence bounds on and uncertainty estimates of the resulting risk levels for use in both the Debris Assessment Software and Object Reentry Survival Analysis Tool.

Finding: The reentry hazard programs used by NASA and the European Space Agency to determine the risk to people on the ground from reentering debris differ in how those thresholds are defined. NASA's Object Reentry Survival Analysis Tool defines a "casualty" as personal injury, whereas ESA models equate a "casualty" with death.

Recommendation: NASA should update the Object Reentry Survival Analysis Tool so that it provides the probabilities of both injury *and* death as standard outputs.

CHAPTER 9: CONJUNCTION ASSESSMENT RISK ANALYSIS AND LAUNCH COLLISION AVOIDANCE

Finding: The computation of the probability of collision for use in an assessment of risk requires the uncertainty parameters in the orbits of the two objects at conjunction, and assumes that these uncertainties are represented by a Gaussian distribution. Research has shown that the uncertainty distribution typically is Gaussian for several days, but when propagating for more than 2 to 3 days it may no longer be Gaussian. In addition, the uncertainties provided by the JSpOC are known to be usually too small, and the probability of collision can be very sensitive to errors in the size of the uncertainty.

Recommendation: NASA should develop a research plan for (1) assessing the impact of inaccuracy in the uncertainty on computations of the probability of collision and on the ensuing risk assessment, and (2) improving the accuracy of the computation of the probability of collision, given the presence of these uncertainty errors.

Finding: The large uncertainties in the launch dispersions (deviations from a planned trajectory) that yield a probability of collision of less than 10^{-5} translate to a very low return on investment in launch collision avoidance (COLA), and funds could probably be used more effectively in some other area of debris mitigation. However, in the event of a collision during launch, the political realities of potentially having done nothing probably mean that the use of COLA needs to continue, especially for crewed launches.

CHAPTER 10: SPACECRAFT ANOMALIES

Finding: Spacecraft anomalies are a direct measurement of both the state of the particulate environment in space and the adequacy of a spacecraft design. However, no formal recording, analyzing, sharing, and reporting procedures exist to take advantage of data on spacecraft anomalies despite that data's potential as valuable information about particulates in a critical size range that is typically not sampled continuously.

Recommendation: NASA should initiate a new effort to record, analyze, report, and share data on spacecraft anomalies in order to better quantify the risk posed by particulates too small to be cataloged yet large enough to disrupt spacecraft operations. The results of this effort would provide general insights into the effects of meteoroids and orbital debris on operational space systems. Eventually, this effort could provide data to upgrade current MMOD models—the Meteoroid Environment Model, Orbital Debris Environment Model, and BUMPER.

CHAPTER 11: ISSUES EXTERNAL TO NASA

Finding: NASA's Orbital Debris Mitigation Standard Practices, including the "25-year rule," and NASA's Procedural Requirements for Limiting Orbital Debris do not uniformly apply to non-NASA missions, launches, and payloads.

Recommendation: NASA should continue to engage relevant federal agencies as to the desirability and appropriateness of formalizing NASA's Orbital Debris Mitigation Standard Practices, including the "25-year rule," and NASA Procedural Requirements for Limiting Orbital Debris as legal rules that could be applicable to U.S. non-NASA missions and private activities.

Finding: The institutions and agreements that have been used to address issues related to orbital debris are primarily political, not legal, in nature. The success of those agreements will thus depend on a complex interplay of good faith; political will; and political, economic, and, sometimes, legal forces.

Recommendation: NASA should continue to engage the international community in efforts to develop cooperation and political will regarding activities concerning orbital debris.

Recommendation: NASA should assess the value of alternative data sets, such as by participating in the not-for-profit Space Data Association, to determine how sharing operator ephemerides might improve the accuracy and efficiency of NASA's Conjunction Assessment Risk Analysis (CARA) by incorporating the best data possible in its CARA process.

Finding: Debris removal activity that involves selecting and removing any given object—debris or otherwise—from space, crosses crucial national and international legal thresholds.

Recommendation: NASA's meteoroid and orbital debris programs should engage the NASA General Counsel's Office and, through that office, the U.S. State Department regarding the legal requirements and diplomatic aspects of active debris removal.

CHAPTER 12: MANAGEMENT AND ORGANIZATIONAL ISSUES

Finding: NASA's management structure has not kept pace with the expanding responsibilities of its MMOD programs. Consequently, the MMOD programs do not have a single management and budget point that can efficiently coordinate all of the current and planned activities and establish clear priorities.

Recommendation: NASA should review the current management structure of its MMOD programs in order to achieve better coordination, provide improved central decision making, and establish a framework for setting priorities. This framework should include a major interface with Congress, other federal and state agencies, and the public.

Finding: NASA's MMOD researchers do not consistently communicate the results of their work to the scientific community, with the result that users of NASA's codes and models have less understanding regarding the underlying assumptions and intricacies in each code and model.

Recommendation: NASA should encourage its MMOD researchers to more fully communicate the results of their work and their development activities, such as in appropriate peer-reviewed publications when possible, so that users of NASA's codes and models gain a greater appreciation for and more clearly understand the underlying assumptions and intricacies in each code and model.

Finding: Nearly all of NASA's MMOD programs are only one person deep in staffing. This shortage of staffing makes the programs highly vulnerable to budget reductions or changes in personnel. Further reductions in real budgetary support over the coming years could threaten the viability and scope of ongoing MMOD programs.

Recommendation: NASA should develop a formal strategic plan that provides the basis for prioritizing the allocation of funds and effort over various MMOD program needs. Among the potential research needs and management issues to be considered is the selection listed in Box 12.1. The strategic plan should consider short- and long-term objectives, a schedule of benchmark achievements to be accomplished, and priorities among them. Stakeholders should be engaged to help develop and review this plan. Finally, the MMOD strategic plan should be revised and updated at regular intervals.

CHAPTER 13: PREPARING FOR THE FUTURE

Finding: The long-lived problem of growth in the orbital debris population as a result of debris self-collision and propagation requires that NASA take a long-term perspective to safeguard the space environment for future generations.

Finding: Although the meteoroid and orbital debris environment may be manageable at present, debris avoidance, mitigation, surveillance, tracking, and response all require money. At present, these costs usually come in the form of additional spacecraft mass and fuel and in the maintenance of debris surveillance systems. Such costs are usually absorbed in the budgets for space mission design, operations, and, in the case of commercial activities, insurance premiums. In the absence of appropriate meteoroid and orbital debris management to deal with the issue, these costs may grow over time. Although they can serve to highlight the importance of NASA's debris measurement and monitoring activities, at present these costs are not routinely measured and reported.

Finding: The cost of replacing spacecraft has been used as a measure of the economic harm of a catastrophic debris impact but may underestimate the full cost of harm for two reasons: (1) actual replacement may be difficult because of funding, launch window limitations, or other constraints; and

(2) replacement cost, insurance premiums, and other measures of the cost incurred to protect a spacecraft understate the full cost to society as a whole if that spacecraft, damaged by a meteoroid or orbital debris, itself generates debris that then creates potential harm to other spacecraft.

Recommendation: NASA should lead public discussion of the space debris problem to emphasize debris as a long-term concern for society that must continue to be addressed today. Necessary steps include improvements in long-term modeling, better measurements, more regular updates of the debris environment models, and other actions to better characterize the long-term evolution of the debris environment.

Recommendation: NASA should join with other agencies to develop and provide more explicit information about the costs of debris avoidance, mitigation, surveillance, and response. These costs should be inventoried and monitored over time to provide critical information for measuring and monitoring the economic impact of the meteoroid and orbital debris problem, signaling when mitigation guidelines may need revision, and helping to evaluate investments in technology for active debris removal.

Appendixes

A

Letter of Request

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

April 26, 2010

Reply to Attn of: Office of Safety and Mission Assurance

Dr. Raymond A. Colladay
Chair, Aeronautics and Space Engineering Board
National Research Council
500 5th Street, NW
Washington, DC 20001

Dear Dr. Colladay:

The White House Office of Management and Budget and Office of Science and Technology Policy have requested that the NASA Administrator "establish a National Research Council [NRC] study of opportunities for NASA to enhance the benefits delivered by its orbital debris program in the context of a fairly constrained budget environment."

For the past two decades, NASA has built a robust program to evaluate and limit the generation of orbital debris (OD) and the risk to NASA spacecraft associated with OD and micrometeoroids (MM). NASA's OD and MM programs are recognized worldwide, yet with the growth of orbital debris over the past few years, we recognize the responsibility to use our capabilities and assets to support not just NASA needs, but also to support, as a national resource, other national and international OD and MM activities. The NRC generated foundational studies of these issues in 1989, 1995, and 1997, all of which form the basis for NASA's role in OD and MM. Therefore, we request that the NRC conduct a study to:

- Review existing NASA policy/efforts and organization with regards to OD and MM, including:
    - Modeling and simulation
    - Detection and monitoring
    - Protection
    - Mitigation
    - Reentry
    - Collision Assessment Risk Analysis and Launch Collision Avoidance
    - Interagency cooperation
    - International cooperation
    - Cooperation with the commercial space industry
- Assess whether NASA should initiate work in any new OD/MM areas.
- Recommend whether NASA should increase or decrease effort, or change the focus of, any of its current MM/OD efforts (within a fairly constrained budget) to improve the office's ability to serve NASA and other national and international activities.

I would like to request that NRC submit a plan to NASA for this study. NASA will provide a review of current OD and MM efforts and associated data sources to NRC at an early opportunity. The results of this study will be of the highest value to NASA in formulating the FY-2013 budget. We will need the findings and recommendations review completed by March 31, 2011. Once agreement with NRC on the scope and cost of the proposed study has been achieved, the NASA Contracting Officer will issue a task order for implementation. Mr. John W. Lyver, IV, will be the NASA technical point of contact for this effort and may be reached at (202) 358-1155 or by e-mail at JLyver@NASA.GOV.

Sincerely,

Bryan O'Connor

Bryan O'Connor
Chief, Safety and Mission Assurance

B

Statement of Task

The National Research Council, under the auspices of the Aeronautics and Space Engineering Board, will establish an ad hoc committee to assess NASA's orbital debris programs and provide recommendations on potential opportunities for enhancing their benefit to the nation's space program.

The committee will:

1. Review NASA's existing efforts, policies, and organization with regard to orbital debris and micrometeoroids, including efforts in the following areas:

    - Modeling and simulation;
    - Detection and monitoring;
    - Protection;
    - Mitigation;
    - Reentry;
    - Collision assessment risk analysis and launch collision avoidance;
    - Interagency cooperation;
    - International cooperation;
    - Cooperation with the commercial space industry.

2. Assess whether NASA should initiate work in any new orbital debris or micrometeoroid areas.
3. Recommend whether NASA should increase or decrease effort in, or change the focus of, any of its current orbital debris or micrometeoroid efforts to improve the programs' abilities to serve NASA and other national and international activities.

The committee should assume that the programs will be operating in a constrained budget environment.

The study will result in two reports. The first will be a workshop report and the second will be the committee's final report at the conclusion of the study.

This project is sponsored by NASA.

C

Committee and Staff Biographical Information

MEMBERS, COMMITTEE FOR THE ASSESSMENT OF NASA'S ORBITAL DEBRIS PROGRAMS

DONALD J. KESSLER, *Chair,* retired from NASA as a senior scientist for orbital debris research. He has more than 30 years of experience in scientific research associated with orbital debris, meteoroids, and interplanetary dust, especially in relation to developing mathematical models, deriving collision probabilities, using sampling techniques, and defining the space environment. Mr. Kessler was a consultant to NASA through Lockheed on orbital debris models and to Prairie View A&M University on orbital debris course development. He worked at NASA's Johnson Space Center as a senior scientist for orbital debris research in the Solar System Exploration Division, where he coordinated NASA's orbital debris research program. He also participated in national and international reviews of other agencies' orbital debris programs and participated in establishing the Inter-Agency Space Debris Coordination Committee, an international agency to address orbital debris issues. He also developed orbital debris models; recommended and developed experiments to test models; analyzed orbital debris data; conducted classes, workshops, and symposia on orbital debris; and recommended cost-effective techniques to control orbital debris. Mr. Kessler modeled interplanetary meteoroid environments, flight control of Skylab experiments, and atmospheric environments, and he developed early orbital debris models and began establishing the need for an orbital debris program. He participated in U.S. Air Force (USAF) and Strategic Defense Command tests and measurements programs, as well as in studies on orbital debris by various organizations, such as the USAF Scientific Advisory Board, AIAA, the Office of Technology Assessment (OTA), and the Government Accountability Office. Mr. Kessler has published approximately 100 technical articles or extended abstracts on meteoroids and orbital debris and is a contributing author or editor of 10 major reports. He was the managing editor for *Space Debris,* an international journal. He received the IAASS Jerome Lederer Space Safety Pioneer Award, the AIAA Losey Atmospheric Sciences Award in 2000, and the NASA Medal for Exceptional Scientific Achievement. Mr. Kessler received his B.S. in physics from the University of Houston.

GEORGE J. GLEGHORN, *Vice Chair,* is an independent consultant who retired as vice president and chief engineer of TRW Space and Technology Group, now a part of Northrop Grumman. During his 37 years at TRW, he contributed to a wide range of distinguished spacecraft: Pioneer I, the first NASA spacecraft; Pioneer 5, which reported the first data received from interplanetary space; Intelsat III, the first satellite to broadcast live television worldwide; the Orbiting Geophysical Observatory; and NASA's Tracking and Data Relay Satellite. He contributed to Pioneer 6, Pioneer 10, and Pioneer 11 and to the development of the Atlas, Thor, and Titan ballistic missiles.

Prior to TRW, Dr. Gleghorn worked at Hughes Aircraft and at the Jet Propulsion Laboratory, and he served as a naval officer in the Korean War. He is a member of the NAE, a fellow of AIAA, and a member of the Institute of Electrical and Electronics Engineers (IEEE). He has also been a member of independent design and readiness review groups on the Hubble Space Telescope refurbishment mission, the Cassini/Huygens orbiter, the probe of Titan, and the Chandra X-Ray telescope spacecraft. Dr. Gleghorn holds a B.S. in electrical engineering from the University of Colorado and M.S. and Ph.D. degrees in electrical engineering and mathematics from the California Institute of Technology. He was a member of the NASA Aerospace Safety Advisory Panel for 10 years and the NRC National Weather Service Modernization Committee, the Committee on Membership, the Aerospace Engineering Peer Committee, the Committee on International Space Station Meteoroid/Debris Risk Management, and the Committee on Space Debris.

KYLE T. ALFRIEND is the TEES Distinguished Research Chair and Professor in the Department of Aerospace Engineering at Texas A&M University. His areas of research include astrodynamics, satellite altitude dynamics and control, space debris, space surveillance, and space systems engineering. Dr. Alfriend has received the American Association for the Advancement of Science (AAAS) International Scientific Cooperation Award, the AIAA Mechanics and Control of Flight Award, and the American Astronautical Society Dirk Brouwer Award. He is a member of the NAE and a fellow of AIAA. Dr. Alfriend earned his M.S. in applied mechanics from Stanford University and his Ph.D. in engineering mechanics from Virginia Tech. He has served as a member of the NRC's Aeronautics and Space Engineering Board and of the Committee on the Future of the U.S. Aerospace Infrastructure and Aerospace Engineering Disciplines to Meet the Needs of the Air Force and the Department of Defense.

MICHAEL J. BLOOMFIELD is vice president and general manager of space systems at Oceaneering Space Systems. Prior to joining Oceaneering, he was vice president for Houston operations at Alliant Techsystems, Inc. (ATK). Mr. Bloomfield is a veteran astronaut of three space shuttle flights. Selected as a NASA astronaut in 1994, he served as a pilot on STS-86 and STS-97 and as commander of STS-110. While at NASA he also held important management positions with the astronaut office, including chief instructor astronaut, chief of astronaut safety, and deputy director of flight crew operations. Additionally, Mr. Bloomfield was director of shuttle operations and chief of the shuttle branch. He also served as deputy director of the Flight Crew Operations Directorate before leaving NASA in 2007 to join ATK. Mr. Bloomfield received his B.S. in mechanical engineering from the U.S. Air Force Academy and his M.S. in engineering management from Old Dominion University.

PETER BROWN is a professor at the University of Western Ontario (UWO) and a member of the Western Meteor Physics Group. He studies small bodies of the solar system, with a particular emphasis on meteors, meteorites, meteoroids, and asteroids. His research interests include answering basic questions about the origin and evolution of small bodies in the solar system, such as the origin of meteoroids (comets/asteroids/interstellar and the proportions of each), the origin of meteorites, the physical structure of meteoroids (bulk density/dustballs and what this says about their origin), and the flux and interaction of larger meteoroids at Earth (meteorites, breakup in the atmosphere). Dr. Brown has received the UWO Governor General's Gold Medal and the Plaskett Medal of the Canadian Astronomical Society and the Royal Astronomical Society of Canada, is the Canada Research Chair in Meteor Science, and won an Ontario Distinguished Researcher Award. He earned his B.Sc. in honors physics from the University of Alberta and his M.Sc. and Ph.D. in physics from the UWO.

RAMON L. CHASE is an associate at Booz Allen Hamilton. He has worked on three new concept efforts: the Fly back Booster System, the Point-to-Point Delivery System, and the Transatmospheric Vehicle. He is also the DARPA representative to the Joint NASA DARPA Horizontal Launch Initiative study advisory group. Previously, he was a principal and division manager at ANSER, where he participated in the development of a National Hypersonic Roadmap and an Air Force Integrated Space Architecture. He has served as a study leader at General Research Corporation and as a propulsion lead to the Jupiter Orbiter Planetary Spacecraft Preliminary Design Team at California Institute of Technology's Jet Propulsion Laboratory. Mr. Chase has written more than 30 technical papers on advanced space transportation systems, military space planes, single stage-to-orbit launch vehicles, orbital transfer vehicles, technology readiness assessment, and advanced propulsion systems. He is an AIAA associate fellow and has served on the AIAA Hypersonics Program Committee and the AIAA Space Transportation Technical Committee. He also chaired the Society of Automotive Engineers (SAE) Hypersonic Committee and SAE Space Transportation Committee. Mr. Chase received an M.A. in public administration from the University of California.

SIGRID CLOSE is an assistant professor in the department of aeronautics and astronautics at Stanford University. Prior to joining Stanford, Dr. Close was a project leader at Los Alamos National Laboratory and a technical staff member at the Massachusetts Institute of Technology's (MIT's) Lincoln Laboratory, where she led programs to characterize meteoroids and meteoroid plasma using high-power radars. She was also the lead space physicist for spacecraft monitoring and unplanned space surveillance events and was a project leader for characterizing and modeling ionospheric plasma instabilities. Dr. Close's current research area is in space weather and satellite systems, which includes characterizing and mitigating environmental risks to spacecraft; detecting and characterizing interstellar dust; signal processing and monitoring using radio-frequency satellite systems; and plasma modeling for remote sensing. Her honors and awards include the Joe D. Marshall Award, given by the Air Force Technical Applications Center for Outstanding Technical Briefing; MIT Lincoln Scholar; and first place in the student paper competition at the International Union of Radio Science. She was the vice chair of Commission G of the International Union of Radio Science. Dr. Close received her Ph.D. in astronomy (space physics) from Boston University.

JOANNE IRENE GABRYNOWICZ is director of the National Center for Remote Sensing, Air, and Space Law at the University of Mississippi and is editor-in-chief of the *Journal of Space Law*. Dr. Gabrynowicz teaches space law and remote sensing law and was a founding faculty member of the University of North Dakota Space Studies Department. She has served as the dean of the NASA Space Academy at Goddard Space Flight Center, as the managing attorney of a law firm, and as an official observer for the International Astronautical Federation to the United Nations' Committee on the Peaceful Uses of Outer Space. She was a member of the International Institute of Space Law delegation to the Unidroit Committee of Governmental Experts for the Preparation of a Draft Protocol to the Convention on International Interests in Mobile Equipment on Matters Specific to Space Assets. Dr. Gabrynowicz is the organizer and chair of the Federal Advisory Committee for the National Satellite Land Remote Sensing Data Archive, and she served as a member of the OTA's Earth Observations Advisory Panel and the Department of Commerce Advisory Committee on Commercial Remote Sensing. She advised the Eisenhower Institute on its study "The Future of Space—the Next Strategic Frontier." She is a member of the International Society for Photogrammetry and Remote Sensing International Policy Advisory Committee, the American Bar Association, the Forum on Aviation and Space Law, the New York State Bar, the International Institute of Space Law, and Women in Aerospace, among other groups. Dr. Gabrynowicz received her B.A. from Hunter College and her J.D. from the Yeshiva University Cardozo School of Law.

ROGER E. KASPERSON is a research professor and distinguished scientist at Clark University. He also taught at the University of Connecticut and Michigan State University. He has written widely on issues connected with risk analysis, risk communication, global environmental change, risk and ethics, and environmental policy. Dr. Kasperson has been a consultant or advisor to numerous public and private agencies on energy and environmental issues and served on various committees of the NRC and the Council of the Society for Risk Analysis. He chaired the International Geographical Union Commission on Critical Situations/Regions in Environmental Change. He was vice president for Academic Affairs at Clark University and was elected director of the Stockholm Environment Institute. He served as co-chair of the scientific advisory committee of the Potsdam Institute for Climate Change and is on the Scientific Steering Committee of the START Programme of the International Geosphere-Biosphere Programme. Dr. Kasperson is a member of the NAS and the American Academy of Arts and Sciences. He has been honored by the Association of American Geographers for his research on hazards and is a recipient of the Distinguished Achievement Award of the Society for Risk Analysis. He received his Ph.D. from the University of Chicago.

T.S. KELSO is currently a senior research astrodynamicist for the Center for Space Standards and Innovation (CSSI) in Colorado Springs, Colorado. He has nearly 30 years of experience in space education, research, analysis, acquisition, development, operations, and consulting with organizations such as the Air Force Space Command Space Analysis Center; NASA's Near-Earth Object Science Definition Team; the Air Force Chief of Staff's SPACECAST 2020 and Air Force 2025 future studies; and the Air Force Satellite Control Network. Dr. Kelso has taught on the faculty at the Air War College; the Air Command and Staff College; the Airpower Research Institute; the College of Aerospace Doctrine, Research, and Education; and the Air Force Institute of Technology. He has supported the space surveillance community by operating electronic data dissemination systems to provide the North American Aerospace Defense Command two-line orbital element sets, associated orbital models, documentation, software, and educational materials to users around the world. Dr. Kelso received a B.S. in both physics and mathematics from the U.S. Air Force Academy, an M.B.A. in quantitative methods from the University of Missouri, Columbia, an M.S. in space operations from the Air Force Institute of Technology, and a Ph.D. in mechanical engineering (operations research) from the University of Texas, Austin.

MOLLY K. MACAULEY is a senior fellow and research director at Resources for the Future, where her research has included studies on economics and policy issues of outer space, the valuation of non-priced space resources, the design of incentive arrangements to improve the use of space resources, and the appropriate relationship between public and private endeavors in space research, development, and the commercial enterprise. Dr. Macauley has also served as a visiting professor in the Department of Economics at Johns Hopkins University. She was elected to the International Academy of Astronautics and was selected as a "Rising Star" by the National Space Society. She is on the board of trustees of the National Center for Atmospheric Research and on the board of directors of the American Astronautical Society and the Thomas Jefferson Public Policy Program of the College of William and Mary. She has testified frequently before Congress and serves on many national-level committees and panels. Dr. Macauley earned her B.A. in economics from the College of William and Mary and her M.S. and Ph.D. in economics from Johns Hopkins University. She is a member of the NRC's Space Studies Board and has previously served on the NRC's Aeronautics and Space Engineering Board, the Panel on Earth Science Applications and Societal Needs, the Science Panel of the Review of NASA Strategic Roadmaps, and the Committee on a Survey of the Scientific Use of the Radio Spectrum.

DARREN S. McKNIGHT is the technical director at Integrity Applications, Inc. (IAI). He is focused on space systems/environment analysis, sustainable energy modeling, innovation practices, visualization solutions, and data analytics. Before coming to IAI, Dr. McKnight served as senior vice president and director of science and technology strategy at Science Applications International Corporation and as chief scientist at Agilex Technologies. His responsibilities included technical collaboration corporate-wide, strategic technology investments (including independent research and development), and validating innovation methodologies. Dr. McKnight has served recently on the Defense Science Board Summer Study on 21st Century Strategic Technology Vectors, National Science Foundation's (NSF's) Industry Expert Panel on Industrial R&D, Harvard Business Review Advisory Council, National Knowledge and Intellectual Property Management Task Force, and IBM's Global Innovation Outlook Team. He has coauthored two technical books, *Artificial Space Debris* and *Chemical Principles Applied to Spacecraft Operations*. Dr. McKnight received his bachelor's degree from the U.S. Air Force Academy in engineering sciences, his master's degree from the University of New Mexico in mechanical engineering, and his doctorate from the University of Colorado in aerospace engineering sciences.

WILLIAM P. SCHONBERG is a professor and chair of the civil, architectural, and environmental engineering department at Missouri University of Science and Technology. He has 25 years of teaching and research experience in shock physics, spacecraft protection, hypervelocity impact, and penetration mechanics. The results of his research have been applied to a wide variety of engineering problems, including the development of orbital debris protection systems for spacecraft in low Earth orbit, kinetic energy weapons, the collapse of buildings under explosive loads, insensitive munitions, and aging aircraft. Dr. Schonberg has published more than 65 papers in referred journals and has presented nearly 65 papers at a broad spectrum of international scientific and professional meetings. He is a recipient of the AIAA Lawrence Sperry Award and of the Charles Sharpe Beecher Prize from the Institution of Mechanical Engineers, is a fellow of the American Society of Mechanical Engineers and the American Society of Civil Engineers, and is an AIAA associate fellow. He received his B.S.C.E. from Princeton University and his M.S. and Ph.D. from Northwestern University. Dr. Schonberg served on the NRC's Committee on Space Shuttle Meteoroid/Debris Risk Management.

STAFF

PAUL JACKSON, *Study Director,* is a program officer for the Aeronautics and Space Engineering Board (ASEB). He joined the NRC in 2006 and was previously a media relations contact for the Office of News and Public Information. He is the study director for a number of ASEB's projects, including proposal reviews for the state of Ohio and this project. Mr. Jackson earned a B.A. in philosophy from Michigan State University in 2002 and an M.P.A in policy analysis, economic development, and comparative international affairs from Indiana University in 2006.

LEWIS B. GROSWALD, research associate, joined the Space Studies Board (SSB) as the Autumn 2008 Lloyd V. Berkner Space Policy Intern. Mr. Groswald is a graduate of George Washington University, where he received a master's degree in international science and technology policy and a bachelor's degree in international affairs, with a double concentration in conflict and security and Europe and Eurasia. Following his work with the National Space Society during his senior year as an undergraduate, Mr. Groswald decided to pursue a career in space policy, with a focus on educating the public on space issues and formulating policy.

JOHN F. WENDT joined the NRC as a part-time, off-site senior program officer for ASEB in 2002. His main activities have involved proposal evaluations for the Air Force Office of Scientific Research and the state of Ohio. He retired in 1999 as director of the von Karman Institute (VKI) for Fluid Dynamics. The VKI is a NATO-affiliated international postgraduate and research establishment located in a suburb of Brussels, Belgium. As director, Dr. Wendt's main responsibility was to ensure the continued excellence of the institute's teaching and research programs by providing effective leadership and administrative and financial management. Dr. Wendt's career at the VKI began as a postdoctoral researcher in 1964. He served as head of the Aeronautics/Aerospace Department and dean of the faculty prior to becoming director in 1990. His research interests were rarefied gas dynamics, transonics, high angle of attack aerodynamics, and hypersonic reentry, including major inputs to the European Hermes space shuttle program in the 1980s. Dr. Wendt has served as a consultant to the U.S. Air Force, NATO, and the European Space Agency. He is a fellow of the American Institute of Aeronautics and Aerospace. Dr. Wendt received a B.S. degree in chemical engineering from the University of Wisconsin and M.S. and Ph.D. degrees in mechanical engineering and astronautical sciences from Northwestern University.

CATHERINE A. GRUBER, editor, joined the SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and also worked as an outreach assistant for the National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

ANDREA M. REBHOLZ joined the ASEB as a program associate in January 2009. She began her career at the National Academies in October 2005 as a senior program assistant for the Institute of Medicine's Forum on Drug Discovery, Development, and Translation. Before joining the Academies, she worked in the communications department of a D.C.-based think tank. Ms. Rebholz graduated from George Mason University's New Century College in 2003 with a B.A. in integrative studies–event management and has more than 9 years of experience in event planning.

RACHAEL ALEXANDROFF grew up in Toronto, Canada, and is currently a rising senior at Princeton University. She is pursuing a major in astrophysics with a certificate in planets and life. On campus she is the president of the Astrobiology Club and a participant in the women in science at Princeton focus group. She has done research in the areas of planetary statistics and active galactic nuclei, including an internship in the summer of 2010 at the

Joint Institute for VLBI in Europe. Her passion for space exploration began at the age of seven and her interest in science policy developed through classes in science journalism and environmental public policy. After graduation in the spring of 2012, Ms. Alexandroff hopes to continue her studies by pursuing a Ph.D. in astrophysics.

KATIE DAUD is a senior at Bloomsburg University of Pennsylvania with a triple major in planetary science, Earth science, and political science. She serves as the president of the Astronomy Club and as senator for the Community Government Association. She did research for the Smithsonian National Air and Space Museum on lunar tectonics. Ms. Daud is interested in combining both her passion for space exploration and her skills in policy to work for NASA's Office of Legislative and Intergovernmental Affairs.

DALAL NAJIB is the Christine Mirzayan Science and Technology Policy Graduate Fellow with the ASEB. Dr. Najib recently completed her Ph.D. in space physics at the University of Michigan (Department of Atmospheric, Oceanic, and Space Sciences) on modeling the interaction of non-magnetized planets (Mars, Venus) with the solar wind, working with Dr. Andrew F. Nagy. During her doctoral work, she developed a new three-dimensional multi-fluid magnetohydrodynamic model and applied it to Mars and Venus. In parallel, she also completed a master's of public policy from the Gerald Ford School of Public Policy at the University of Michigan with a focus on science and technology policy. Dr. Najib received her undergraduate degree in aerospace and aeronautical engineering from Supaero (Toulouse, France). She is interested in space policy, general science and innovation policy, and efforts to promote cooperation between international science communities.

MICHAEL H. MOLONEY is the director of the SSB and the Aeronautics and Space Engineering Board at the NRC. Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Before joining the SSB and ASEB in April 2010, he was associate director of the BPA and study director for the Astro2010 decadal survey for astronomy and astrophysics. In addition to his professional experience at the NRC, Dr. Moloney has more than 7 years of experience as a foreign-service officer for the Irish government and served in that capacity at the Embassy of Ireland in Washington, D.C., the Mission of Ireland to the United Nations in New York, and the Department of Foreign Affairs in Dublin, Ireland. A physicist, Dr. Moloney did his graduate Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

D

Acronyms

AAS	American Astronomical Society
ADR	active debris removal
AFSPC	Air Force Space Command
AIAA	American Institute of Aeronautics and Astronautics
ALTAIR	ARPA Long-Range Tracking and Instrumentation Radar
Ames	Ames Research Center
AMOR	Advanced Meteor Orbit Radar
APA	Administrative Procedure Act
ARTEMIS	Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun
ASAT	anti-satellite
ASEB	Aeronautics and Space Engineering Board
BLE	ballistic limit equation
CA	Conjunction Assessment
CARA	Conjunction Assessment Risk Analysis
CEOS	Committee on Earth Observations Satellites
COLA	Launch Collision Avoidance
COSPAR	Committee on Space Research
DARPA	Defense Advanced Research Projects Agency
DAS	Debris Assessment Software
DLR	German Aerospace Center
DOD	Department of Defense
DPE	damage predictor equation
EMP	electromagnetic pulse
ESA	European Space Agency

ESD	electrostatic discharge
EVA	extravehicular activity
EVOLVE	2-dimensional Evolutionary Debris Model
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
GEO	geosynchronous/geostationary Earth orbit
GPM	Global Precipitation Measurement (mission)
GSFC	Goddard Space Flight Center
HAX	Haystack Auxiliary
HITF	Hypervelocity Impact Technology Facility
HPLA	high power large aperture radar
HRMP	Harvard Radio Meteor Project
HST	Hubble Space Telescope
HVIT	Hypervelocity Impact Technology
IADC	Inter-Agency Space Debris Coordination Committee
IAF	International Astronautical Federation
IDP	interplanetary dust particle
IFM	Interplanetary Flux Model
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
JSC	Johnson Space Center
JSpOC	Joint Space Operations Center
KSC	Kennedy Space Center
LARC	Langley Research Center
LDEF	Long Duration Exposure Facility
LEGEND	LEO-to-GEO Environment Debris model
LEO	low Earth orbit
LMT	Liquid Mirror Telescope
LSC	UNCOPUOS Legal Subcommittee of Committee on the Peaceful Purposes of Space
LSP	Launch Services Program
MCAT	Meter-Class Autonomous Telescope
MCSurv	Manned Spacecraft and Crew Survivability
MEM	Meteoroid Environment Model
MEO	Meteoroid Environment Office
MMOD	meteoroid and orbital debris
MODEST	Michigan Orbital Debris Survey Telescope
MSCSurv	Manned Spacecraft and Crew Survivability code
MSFC	Marshall Space Flight Center
NaK	sodium potassium
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

NORAD	North American Aerospace Defense Command
NRC	National Research Council
NRO	National Reconnaissance Office
OCM	Orbit Conjunction Messages
OCT	Office of the Chief Technologist
OD	orbital debris
ODA	orbital debris assessment
ODPO	Orbital Debris Program Office
OMB	Office of Management and Budget
ORDEM	Orbital Debris Environment Model
ORSAT	Object Reentry Survival Analysis Tool
OSTP	Office of Science and Technology Policy
P_c	probability of collision
PRA	probabilistic risk analysis/assessment
PSFT	Propulsion Systems Foundation Technology
PVDF	polyvinylidene fluoride
RCS	radar cross-section
RORSAT	Radar Ocean Reconnaissance Satellite
SBM	standard breakup model
SBRAM	Satellite Breakup Assessment Model
SDA	Space Data Association
SDC	Space Data Center
SEM	Size Estimation Model
SGP4	Simplified General Perturbations 4
SNR	signal-to-noise ratio
SOCIT	Satellite Orbital Debris Characterization Impact Test
SP	special perturbations
SSN	Space Surveillance Network
STD	NASA Technical Standard
STSC	UNCOPUOS Science and Technology Subcommittee
TLE	two-line element set
TRL	technology readiness level
UN	United Nations
UNCOPUOS	UN Committee on the Peaceful Uses of Outer Space
UNGA	UN General Assembly
USAF	U.S. Air Force
USSR	Union of Soviet Socialist Republics
USSTRATCOM	U.S. Strategic Command

E

Glossary

25-year rule—a nonbinding guideline that stipulates that the post-operational orbital life of spacecraft orbiting below 2,000 km be restricted to 25 years.

ablation—the process whereby material is heated, vaporized, and lost from the surface of a projectile that is penetrating Earth's atmosphere.

absolute magnitude—a measure of the luminosity a meteor would have as observed from a distance of 100 km.

AFI 91-217—Air Force Instruction 91-217 that along with Air Force Instruction 91-202 (U.S. Air Force Mishap Prevention Program) provides guidance for the development of a comprehensive mishap prevention program for current and future space systems, including the minimum risk probability parameters required for safe space operations and testing.

aperture—for instruments that collect electromagnetic radiation, the size of an instrument's collecting area.

apogee—point in an orbit that is farthest from Earth.

astrodynamics—the study of the motion of human-made objects in space, subject to both natural and artificially induced forces

astronomical unit **(AU)**—mean distance of Earth from the Sun. Approximately 1.5×10^8 km.

atmospheric drag—resistance in the atmosphere caused when an object interacts with atmospheric particles.

NOTE: The definitions given in this appendix are drawn from such sources as *Space Vehicle Design* by Griffin and French (American Institute of Aeronautics and Astronautics, 1991); *IUPAC Compendium of Chemical Terminology* (1991); *Traces of catastrophe: A Handbook of Shock-Metamorphic Effects in Terrestrial Meteororite Impact Structures* by Bevan French (Lunar and Planetary Institute, 1998); *NASA Handbook 8719.14: Handbook for Limiting Orbital Debris*; and *Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decisions Making* by Drouin et al; and from material available at sources such as www.nasa.gov, adsabs.harvard.edu, ntrs.nasa.gov, and www.celestrak.com.

ballistic limit—either the combination of geometry and material properties of a target (such as a debris shield) that is necessary to prevent a given impacting particle from perforating it at a specified velocity, or the minimum size of a particle that perforates a given target at a specified velocity, or the velocity beyond which a given particle will perforate a given target.

ballistic limit equation (BLE)—equation defining a curve (often referred to as a ballistic limit curve, or BLC) that is typically plotted in projectile diameter-impact velocity space and is a line of demarcation between those diameter-velocity combinations that result in target perforation and those combinations that do not.

breakup—destructive fragmentation of a space object. Breakups may be either accidental or intentional.

BUMPER—a NASA semi-empirical computer code that calculates the probability of system failure (e.g., spacecraft wall penetration) in light of specific design features.

cataloging—process of detecting, identifying, and determining the discrete orbit of a space object.

characteristic length—the arithmetic mean of the three major mutually perpendicular dimensions of an object.

cis-martian region—the region of space between the orbit of Earth and Mars.

confidence interval—the probability that the true number lies in a set of values.

conjunction—the point of closest approach of two objects.

conjunction (assessment risk) analysis—the process performed for mitigating the risk of an operational satellite colliding with a cataloged object. Known as Conjunction Assessment Risk Analysis (CARA) at NASA/GSFC for robotic spacecraft and conjunction analysis (CA) at JSC for the International Space Station and future U.S. human spacecraft operations.

cross-tagged—indicating a situation in which the observations for two (or more) closely separated objects are associated with the tracks of the other object(s).

damage predictor equation (DPE)—an equation that predicts damage (e.g., hole diameter, crater depth) to system components in terms of an impacting particle's density, velocity, and angle of impact and the geometric and material properties of the target.

debris—see "orbital debris."

Debris Assessment Software (DAS)—suite of tools (ORDEM, orbit propagators, and ballistic limit equations) that produces a first-order assessment of the risk of human casualty associated with uncontrolled space vehicle reentries.

decay—natural loss of altitude of a space object, culminating in reentry into Earth's atmosphere.

deorbit—deliberate, forced reentry of a space object into Earth's atmosphere by applying a retarding force, usually via a propulsion system.

destructive scattering—for electromagnetic waves that interact, the interference that produces a net decrease in the amplitude of the resultant waves.

electromagnetic pulse (EMP)—a short but intense burst of electromagnetic energy.

electromagnetic scattering—the process of readmitting energy that was removed from a beam of electromagnetic radiation.

electrostatic discharge (ESD)—a transfer of an electrostatic charge; also known as a shock.

emissivity—the ratio of the amount of radiation emitted by an object to the amount emitted by a blackbody at the same temperature.

ephemerides—plural form of ephemeris; a tabulation of computed positions and velocities (and/or various derived quantities such as right ascension and declination) of an orbiting body at specific times.

ESA Master—a European Space Agency space debris and meteoroid environment model that describes the human-made and natural particulate environment of Earth and its incident flux on user-defined target orbits down to an impactor diameter of 1 micron.

Fast Air Target Encounter Penetration (FATEPEN)—a DOD computer program used in aircraft, vehicle, and ship vulnerability assessment.

flux—the number of objects impacting or passing through a unit area per unit time.

fragmentation—process by which an orbiting space object disassociates and produces debris.

Gaussian distribution—a continuous probability distribution that is often used to approximate a set of real, random values clustered around a single mean value.

GEOPROP—GEO propagator. A general-purpose orbital propagator model that includes in its calculations perturbations due to solar and lunar gravity, radiation pressure, and other major geopotentials.

geosynchronous Earth orbit (GEO)—see “orbital regions.”

graveyard orbit—an orbit into which spacecraft whose operational life have ended are intentionally placed to reduce the probability of collisions, and which currently includes orbits in two regions: higher than 2,000 km but outside GEO, and higher than GEO.

ground injury effects—potential injurious effects caused by the kinetic energy of a surviving debris object as it strikes the ground. Testing and analysis in support of range safety tests are used to estimate the likely injury on the ground if a person is struck by a piece of reentering debris.

Grün et al. interplanetary flux model (IFM)—an empirical compilation of many data sources that is used as the standard reference for meteoroid flux in near-Earth space.

Haystack—a high-power X-band radar that is a part of the Lincoln Laboratory’s Space Surveillance Complex and a contributing sensor to the U.S. Space Surveillance Network.

“height ceiling” effect—altitude cutoff above which a specular radar cannot detect the trails of objects reentering Earth’s atmosphere.

hypervelocity—relative velocity of two objects that, in general, exceeds the speed of sound in solid materials (about 5 km/s) and results in an impact response that is not dominated by material strength effects.

hypoxia—a reduction in the amount of oxygen reaching tissues in the body.

impact plasma—plasma generated from a meteoroid impact event.

inclination—angle between the orbital plane of a space object and the plane of Earth's equator.

ionization efficiency—ratio of the number of ions formed to the number of electrons or photons used in an ionization process.

kinetic energy—the energy of motion.

launch collision avoidance (COLA)—the process of actively screening for potential collisions between a launch vehicle and known, tracked, on-orbit objects from liftoff through the end of the launch phase, and subsequently taking action to avoid any unacceptable conjunctions.

legally binding custom—a complex mix of precedent, practice, intent, and *opinio juris* (general conduct recognized within judicial decisions) within the geopolitical context of a given agreement.

LEO-to-GEO Environment Debris Model (LEGEND)—a NASA statistical, three-dimensional, debris evolutionary model for the study of the long-term debris environment for LEO, HEO, and GEO that provides debris characteristics as functions of time, altitude, longitude, and latitude.

light gas gun—a two-stage projectile launching device that uses a highly compressed light gas (such as hydrogen) to accelerate projectiles to typical speeds of 5-10 km/s under well-controlled conditions.

low Earth orbit (LEO)—see "orbital regions."

luminous efficiency—fraction of total initial energy converted into visible radiation. It is a measure of the source's ability to produce visible light.

Manned Spacecraft and Crew Survivability Code (MSCSurv)—a NASA computer code that calculates the probability of a spacecraft loss given a penetration of the crewed habitation modules.

meteor—phenomenon (involving heat, light, ionization) associated with a meteoroid impacting a planetary atmosphere.

meteoroid—small, solid particles orbiting the Sun, formally defined by the International Astronomical Union as being larger than an atom or molecule and smaller than an asteroid.

Meteoroid Environment Model (MEM)—a NASA semi-empirical computer code for estimating the distribution of meteoroid velocity and direction for near-Earth and interplanetary (Mercury to asteroid belt) natural particulates down to 1 μg, to provide flux on spacecraft surfaces.

Meteoroid Environment Office—NASA's technical lead for defining the meteoroid environment using radar and optical measurements, for performing data analysis, and for developing models that can be used together with tests results from the Hypervelocity Impact Technology Facility at JSC.

microcrater—crater produced on spacecraft surfaces or from rocks on airless solar system bodies on the order of 1 mm in size or smaller.

micrometeoroid—colloquialism for a “small” meteoroid.

mission-related debris—objects dispensed, separated, or released as part of a planned mission.

mission-related object—an object intentionally released from a spacecraft or rocket body during the course of a mission.

Monte Carlo Method—any method that searches for a solution to a problem by generating random numbers using a set of parameters and then determining what percentage of those random numbers possess certain properties.

NASA Technical Standard 8719.14—establishes requirements for (1) limiting the generation of orbital debris, (2) assessing the risk of collision with existing space debris, (3) assessing the potential of space structures to impact the surface of Earth, and (4) assessing and limiting the risk associated with the end of mission of a space object.

“new construction” satellite—a satellite that has features to limit or prevent the creation of orbital debris.

“no explosion” guideline—removing from a space structure at the end of mission stored energy that could result in an explosion or deflagration of the space structure, to preclude generation of new orbital debris after end of mission.

Object Reentry Survival Analysis Tool (ORSAT)—a NASA semi-empirical model for determining survivability of reentering hardware, using a suite of tools that perform trajectory, atmospheric, aerodynamic, thermodynamic, and thermal/ablation physics calculations.

“old construction” satellite—a satellite that does not include features or ways to minimize the creation of orbital debris.

Olympus Satellite—a European Space Agency (ESA) experimental communications satellite that experienced multiple anomalies on August 11, 1993, near the peak of the Perseid meteor shower that year.

orbit—the path taken by an object that revolves around another object. Special orbits include the following:

- **highly elliptical orbit**—an orbit with an eccentricity of greater than 0.5, including geostationary transfer orbit and the Molniya orbits.

- **unbound orbit**—an orbit whose energy with respect to the Sun is greater than zero; all such orbits trace out hyperbolas (or in the limiting case of an orbit with $e = 0$, a parabola) with the Sun at one foci.

orbit conjunction message—a message format that allows communication between government and commercial agencies about spacecraft orbits.

orbital debris—space objects in Earth orbit that are not functional or operational spacecraft, including spent rocket bodies, mission-related objects, fragments from breakups and deterioration, sodium potassium radiator coolant from Russian nuclear-powered spacecraft, and aluminum oxide particles from solid rocket exhaust; such debris can be artificial or natural.

orbital lifetime reduction—acceleration of the natural decay of spacecraft and other space objects’ orbits to reduce the time that they remain in orbit.

orbital regions—space objects travel in a wide variety of orbits at various altitudes. The following are some of the more frequently used orbits:

- **circular semisynchronous orbit**—circular orbit (such as that used by the Global Positioning System) with a period of about 12 hours. The mean altitude of such an orbit is approximately 20,200 km.

- **geostationary Earth orbit**—nearly circular orbit with a period of approximately 1,436 minutes and an inclination close to zero degrees. In such an orbit, the satellite maintains a relatively stable position directly above the equator, at a mean altitude of approximately 35,785 km. In practice, "geostationary" satellites exhibit small orbital eccentricities and slight inclinations, resulting in an apparent wobble about a fixed location.

- **geostationary transfer orbit (GTO)**—elliptical orbit with an apogee around GEO and a perigee in LEO. This orbit is used to transfer spacecraft from LEO to GEO. The rocket bodies used to accomplish this transfer often remain in this orbit after the spacecraft separates and circularizes its orbit using an apogee kick motor.

- **geosynchronous Earth orbit (GEO)**—roughly circular orbit with any inclination and a period of approximately 1,436 minutes.

- **high Earth orbit (HEO)**—any Earth orbit with a mean altitude greater than 2,000 km.

- **low Earth orbit (LEO)**—orbit with a mean altitude of less than 2,000 km.

- **Molniya orbit**—highly elliptical orbit with an inclination of 63.4 degrees (or 116.6 degrees, which has never been used), a period of about 12 hours, apogee above the Northern Hemisphere near geosynchronous altitude, and perigee in the Southern Hemisphere. Molniya orbits have historically been used to provide communications and early-warning services; they are suited to this task because spacecraft in Molniya orbits spend most of their time above the middle latitudes of the Northern Hemisphere.

- **Sun-synchronous orbit (SSO)**—retrograde LEO orbit in which the orbit plane processes at the same rate Earth revolves around the Sun. A spacecraft in SSO experiences the same ground lighting conditions each day, which can be useful for Earth observation missions.

Orbital Debris Environment Model (ORDEM)—a NASA semi-empirical computer code for environment characterization for current and short-term future (~30 years) debris impact flux down to 10 µm in Earth orbit (LEO and GEO) based on returned samples, remote observations, modeling, and historical changes and trends.

payload—the cargo carried by a vehicle.

perigee—point in an orbit that is closest to Earth.

Poisson consensus model—model that consolidates theory, measurements, and assumptions into an average event rate where Poisson statistics apply. This process requires the integration of various statistical distributions (such as velocity, and angle of impact).

polarization—action whereby waves of electromagnetic radiation are limited to vibrations in specific directions.

power-law distribution—also known as the Pareto distribution, which states that smaller objects or events are more common and larger objects or events are rare.

probabilistic risk assessment (PRA)—a process used to determine the overall risk associated with a particular program or a mission stage by factoring in all known risks, and their corresponding uncertainties, if known.

projectile—an object that is propelled forward by an external force.

PROP3D—Propeller Three Dimensional Analysis. A NASA general-purpose orbital propagator model.

protection

- **active protection**—steps taken, once a spacecraft is in orbit, to reduce the level of risk to which it is exposed; includes, for example, the elimination of debris in the path of an orbiting spacecraft, the avoidance of collisions and the removal of large objects to eliminate future potential debris-generating events.

- **passive protection**—steps applied before a spacecraft is launched, including, for example, spacecraft shielding, redundant system design, and orbit selection to lower exposure to particulates.

- **operation protection**—steps designed to protect a spacecraft against damage from particles that are too large to actively protect against or too small to be seen and avoided; includes intelligent spacecraft attitude profiles, and smart working and living arrangements (e.g., placing astronauts in areas not directly exposed to the particulate flux).

radar cross section (RCS)—a measure of how much radar energy is reflected from an object, usually a function of the absolute size of the target, the target's material, and the geometry of the encounter.

radar head echo data—data on radar reflection from plasma that forms in the vicinity of meteoroids.

reentry casualty—as defined by NASA (within ORSAT and DAS models), a person who is injured by reentering space hardware; as defined by the European Space Agency, a person who is killed by a reentering object.

remediation—restoration of a contaminated environment by the removal of the contamination (e.g., orbital debris).

remote sensing—the measurement or acquisition of information on some property of an object or phenomenon, by a recording device that is not in physical or intimate contact with the object or phenomenon under study.

reorbit—intentional action to change a space object's orbit at the end of its operational life. Typically, this process involves putting the space object into an orbit where it is expected to pose a reduced hazard (including both collision and reentry hazards).

risk—the combination of the probability of an event and the consequence of that event.

rocket body—any stage of a launch vehicle (including apogee kick motors) left in Earth orbit at the end of a spacecraft delivery (launch and orbital insertion) sequence.

satellite—a natural or artificial body in orbit around another body, such as a planet.

satellite anomoly—mission-degrading or mission-terminating events affecting on-orbit operational spacecraft.

satellite breakup assessment model (SBRAM)—a NASA computer code used to determine the short-term hazard (hours to days) from a single breakup event and separate from "background risk."

satellite orbital debris characterization impact test (SOCIT)—a series of hypervelocity tests conducted between 1991 and 1992 by the DOD to simulate the hypervelocity breakup of a payload.

self-propagation—chain reaction resulting in an increase in the amount of orbital debris.

signal-to-noise ratio (SNR)—a measurement, in decibels of the strength of a signal compared with the background noise.

size estimation model (SEM)—an algorithm for estimating orbital debris size that relates radar cross section to size.

slag—the remains of the smelting of metallic ore; also produced by solid rocket motors that have aluminum as a fuel source.

"soft law"—a set of rules or guidelines that are not necessarily legally binding but are still legally significant.

solar cycle activity—periodic fluctuations in the energy output of the Sun. High solar output can cause expansion of Earth's atmosphere.

solar flux—a historical representation of past solar flux component levels (i.e., 10.7 cm wavelength) and predicted future levels of intensity.

solid rocket motor—the part of a spacecraft that produces thrust by burning a solid fuel.

spacecraft—orbiting object designed to perform a specific function or mission (e.g., communications, navigation, or weather forecasting).

spacecraft anomaly—an unexpected or unplanned event or incidence that occurs to a spacecraft.

space fence—a U.S. Air Force tracking system that will replace the Naval Space Surveillance Network and will become part of the Air Force Space Surveillance System; it will be able to detect objects in space down to 5 cm in size.

space object—any object in space, including the natural meteoroid environment, as well as orbiting objects such as individual spacecraft, rocket bodies, fragmentation debris, and mission-related objects.

Space Surveillance Network (SSN)—collection of ground-based radar and electro-optical sensors used by the U.S. Space Command to track and correlate human-made space objects.

Space Surveillance System (SSS)—Russian counterpart of the U.S. Space Surveillance Network.

spallation—phenomenon that occurs when a high-velocity impact causes a stress wave to interact with the free back surface of a thick target and possibly eject material from the rear surface of the target without perforating the target.

special perturbations data—data set of higher accuracy obtained using a force model with higher fidelity than CARA/CA.

specific heat—the amount of heat required to raise the temperature of 1 gram of a substance 1 degree Celsius.

spectral energy distribution—the power carried by electromagnetic radiation with a wavelength, as a function of wavelength.

specular-scattering radar—a radar capable of specular scattering, indicating that the radar beam lies perpendicular to the axis of the rail, resulting in Fresnel reflections.

specular trail—trail plasma measured when a meteoroid is traveling perpendicular to the line-of-sight of a radar.

sporadic meteoroid—meteoroid not found in a stream. Although such meteoroids do not have a clear common parentage, the sporadic background meteoroid population as detected at Earth shows strong directionality reflecting the general orbital properties of the parent body population.

SSP 30435—Space Station Program Natural Environment Definition for Design; includes the environmental models used to design the space station as they were defined in 1994.

state vector—provides the location, velocity, and future course that an object will take in space using a 3-dimensional frame of reference.

stream meteoroid—meteoroid with a common, recent (less than 100,000 years) parentage, resulting in all meteoroids associated with the stream following nearly identical heliocentric orbits.

Standard Breakup Model (SBM)—semi-empirical model that determines the number, mass, velocity, and ballistic coefficient distributions of fragments down to 1 mm produced from a breakup event.

terminal velocity—the constant, maximum speed that a falling object reaches when the downward force of gravity equals the upward force of drag**.**

trajectory—the path taken by a falling object.

two-line element set (TLE)—a data set made up of two 69-character lines that enables deducing the position and velocity of a satellite when used in collaboration with NORAD's SGP4/SDP4 orbital model.

uncertainty—lack of knowledge and understanding of the structure of a risk and the connections between the stages of the evolution of a risk.

VAX computer—Virtual Address eXtension computer.

Whipple shield—a type of hypervelocity impact shield used to protect crewed and uncrewed spacecraft from collisions with small particles, typically consisting of two metallic or non-metallic panels placed a small distance apart from each other.

zodiacal light—a dim cone of light produced by scattering of sunlight off interplanetary dust. It can be seen in the night sky above the horizon just before or just after sunset.

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Reprinted Workshop Report

Summary of the Workshop to Identify Gaps and Possible Directions for NASA's Meteoroid and Orbital Debris Programs (National Research Council, The National Academies Press, Washington, D.C., 2011), which summarizes the National Research Council workshop held in March 9-10, 2011, in Fairfax, Virginia, is reprinted here in its entirety. Note that the reprinted report's page numbers reflect the pagination that applies for inclusion in the current report, rather than the pages numbers of the original report.

Summary of the Workshop to Identify Gaps and Possible Directions for NASA's Meteoroid and Orbital Debris Programs

Committee for the Assessment of NASA's Orbital Debris Programs

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

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Preface

The National Research Council (NRC), under the auspices of the Aeronautics and Space Engineering Board, was asked by NASA Chief of Safety and Mission Assurance Bryan O'Connor to assess NASA's meteoroid[1] and orbital debris (MMOD) programs and provide recommendations on potential opportunities for enhancing their benefit to the nation's space program. This request came at the urging of the White House Office of Management and Budget and Office of Science and Technology Policy (see Appendix A).

The NRC assembled the Committee for the Assessment of NASA's Orbital Debris Programs to review NASA's existing efforts, policies, and organization with regard to meteoroids and orbital debris, including its efforts in the areas of modeling and simulation, detection and monitoring, protection, mitigation, reentry, collision assessment risk analysis and launch collision avoidance, interagency cooperation, international cooperation, and cooperation with the commercial space industry. The committee was also asked to provide its opinion as to whether NASA should initiate work in any new MMOD areas and to recommend whether the agency should increase or decrease effort in or change the focus of any of its current meteoroid or orbital debris efforts to improve their ability to serve NASA and other national and international activities. The committee was instructed to assume that the programs will be operating in a constrained budget environment (see Appendix B for the committee's statement of task). Through a series of information-gathering meetings, including the workshop that is the subject of this report, the committee received briefings from representatives of NASA and other federal agencies and foreign space agencies, as well as from other experts in the fields of meteoroids, orbital debris, and aerospace technology.

Although the statement of task refers to a singular NASA program in this field, there are in fact numerous program elements spread across NASA mission centers that address MMOD. For the purposes of this report, these elements are referred to as NASA's MMOD programs.[2] The vast majority of NASA's efforts fall within five program elements (the "programs"), which are:

- *Office of Safety and Mission Assurance, NASA Headquarters:* Provides top-level budget and programmatic management, technical oversight, and coordination within NASA and with other U.S. government entities; advocate to senior NASA management on MMOD;

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[1] This report uses the word "meteoroid" according to its precise definition, rather than the term "micrometeoroid," a colloquialism for "small" meteoroids and an imprecise term that does not cover the full range of sizes or meteoroids. However, to avoid adding a new acronym to the literature and to minimize confusion, the committee retains use of the acronym "MMOD" (micrometeoroid and orbital debris) as a modifier (e.g., MMOD programs).

[2] This term also reflects how the programs were referred to by many panelists and committee members at the workshop.

- *Orbital Debris Program Office, NASA Johnson Space Center:* Performs many duties that are NASA-specific, interagency, and international in nature; within NASA, in charge of aiding all robotic and human spaceflight missions in determining compliance with NASA policy standards regarding orbital debris mitigation and responsible for technical evaluations of all orbital debris assessment reports and end-of-mission plans;
- *Meteoroid Environment Office, NASA Marshall Space Flight Center:* Responsible for the creation and stewardship of meteoroid environment models, tools, and documents relevant to spacecraft operations and design;
- *Hypervelocity Impact Technology Group, NASA Johnson Space Flight Center:* Works to decrease MMOD risk to crew, improve MMOD protection of NASA spacecraft, and decrease the amount of MMOD shielding in terms of cost, volume, and mass; and
- *Robotic Conjunction Assessment Risk Analysis, NASA Goddard Space Flight Center:* Supports robotic missions by conducting risk assessments of possible collisions between spacecraft in orbit of the close approaches predicted by the U.S. Air Force Joint Space Command.

In addition to these established programs, the *National Space Policy of the United States of America,*[3] released in 2010 (henceforth referred to as the 2010 National Space Policy), also calls for NASA to take on research and development into technologies related to orbital debris retrieval and removal. In addition to research and development, the policy also makes maintaining a sustainable space environment a long-term goal of the United States.

Because of the diversity and number of perspectives and entities involved in space activities within the United States, the committee held a public workshop on March 9-10, 2011, in Fairfax, Virginia, as an efficient way to hear from the various stakeholders. The workshop complements other data-gathering meetings held by the committee throughout the course of its study.

The committee's statement of task calls for a summary of the workshop, which is the purpose of this report. The presentations and discussions that took place at the workshop are summarized in this report, although the committee does not offer any findings or recommendations. The committee will detail its findings and offer recommendations in its next, and final, report. The committee maintains responsibility for the overall quality and accuracy of the report as a record of what transpired at the workshop, but views and opinions contained in this workshop report were expressed by the presenters, attendees, or individual committee members as attributed and do not necessarily represent the views of the whole committee.

The committee heard from five panels of presenters at the workshop, each of which was composed of three to five members who spoke for a short period of time. Their names and affiliations are listed in Appendix C. Following the presentations, questions and comments were then solicited, first from the committee members and then from the audience, which consisted of government employees, academics, and representatives of the aerospace industry.

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[3] *National Space Policy of the United States of America,* June 28, 2010, available at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

William Ailor, The Aerospace Corporation,
Ravi B. Deo, EMBR,
John L. Junkins, Texas A&M University,
Chris T.W. Kunstadter, XL Insurance, and
Michael F. Zedd, Naval Research Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse any of the viewpoints or observations detailed in this report. The review of this report was overseen by M. Granger Morgan, Carnegie Mellon University. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

REPRINTED WORKSHOP REPORT

Contents

APPENDIXES

REPRINTED WORKSHOP REPORT

Summary of Remarks Made by Workshop Participants

The workshop was opened by the chair of the Committee for the Assessment of NASA's Orbital Debris Programs, Donald Kessler, who welcomed the guests, provided a synopsis of the overall study underway and the objectives of the workshop, and described the panels that were formed prior to the workshop.

The panels presented at the workshop in the following order:

1. Panel on NASA Meteoroid and Orbital Debris Programs,
2. Panel on NASA Mission Operators,
3. Panel on the Role of NASA's MMOD Programs and Their Relationship to Other Federal Agencies,
4. Panel on MMOD and the Commercial Industry Perspective, and
5. Panel on Orbital Debris Retrieval and Removal.

SESSION 1: NASA METEOROID AND ORBITAL DEBRIS PROGRAMS

The leads for NASA's meteoroid and orbital debris (MMOD) programs, as noted in the Preface, described their organizations, objectives, obstacles to achieving those objectives, and opportunities for advancing the state of the art. The MMOD programs provide a service function, which gives them the capability to go across missions, centers, and agencies in the areas of design assistance, pre-launch review/assessment, launch and on-orbit conjunction assessment, and pre-decommissioning/disposal assistance. The MMOD programs interface with other NASA divisions, U.S. agencies, commercial entities, and international organizations, but there does not appear to be a consolidated research budget for the programs, and NASA does not have the capability to remove existing debris from orbit.

Workshop participants described obstacles to designing spacecraft with reduced risk of damage from MMOD. While extensive research on MMOD effects, mitigation, and elimination has been underway for more than 30 years, and debris can be tracked reliably down to sizes of 10 cm and sometimes less, an issue that has been pervasive since the beginning of the program is that considerable damage to space objects can be caused by particles that are an order of magnitude smaller than 10 cm, which can be more numerous and difficult to eliminate from orbit (Figure 1). This obstacle to fully characterizing the environment sometimes puts NASA in a difficult situation, it was explained, because the agency currently has a gap between detection capabilities and risks inherent to operating in the space environment for many spacecraft systems.

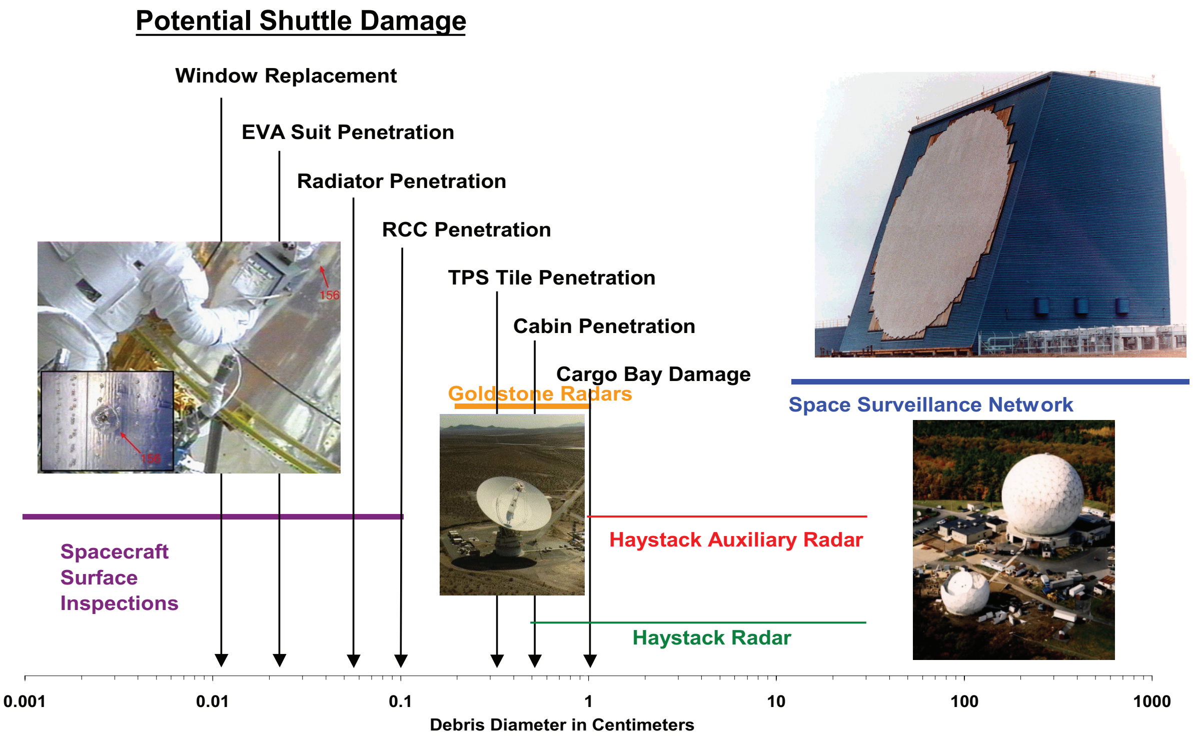

FIGURE 1 Meteoroid and orbital debris detection platforms and capabilities. SOURCE: John Lyver, NASA, presentation at the Workshop to Identify Gaps and Possible Directions for NASA's MMOD Programs, March 9, 2011.

Another obstacle facing NASA is that even for particles that are centimeters in size, the agency lacks a process for determining how particle shape plays a role in the damage that can be caused by an impact. Methods to incorporate particle shape into impact models have not been validated, and hence the application of a safety factor in spacecraft design techniques may result in uncertainty to both weight and physical dimensions of a spacecraft designed to operate in the MMOD environment.

A third obstacle cited by panelists as adding uncertainties in design is that experimental facilities for testing spacecraft damage, including via hypervelocity testing, generally employ spheres or simple shapes made from aluminum. Moreover, typical impact speeds at these test facilities do not exceed speeds of 7-8 km/s, whereas the average relative impact velocity of orbital debris particles in low Earth orbit (LEO) is around 9 km/s, and orbital debris and meteoroids can reach relative impact velocities of up to 15 km/s and 70 km/s, respectively.[1] Although ultra-high-velocity testing facilities exist, they are more expensive than facilities with conventional high-velocity-testing techniques, and they employ particles on the average of several microns in size. Thus extrapolation from such experiments, which do not duplicate debris shape or material properties, introduces even more uncertainties due to a mismatch of collision velocity.

Panelists did point out that the space shuttle and some spacecraft parts returned from orbit, for example solar panels from the Hubble Space Telescope (HST), have exhibited debris damage that can be analyzed, although the conditions of impact (debris shape, size, and impact velocity) are seldom known with precision.

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[1] Eric Christiansen, "Hypervelocity Impact Technology (HVIT) Group," presented at the NRC Workshop to Identify Gaps and Possible Directions for NASA's MMOD Programs, March 9, 2011.

Research by NASA's Orbital Debris Program Office (ODPO) has demonstrated that even if additional spacecraft are not placed in LEO and if the 25-year rule[2] for the maximum lifetime of a satellite is reduced significantly and followed by all agencies, the amount of debris in orbit has already reached the point that a continued increase in debris is likely due to collisions between objects already in orbit, which produce increasing numbers of collision products as time passes. This reality has impressed on policymakers the need to carry out R&D on the retrieval/removal of objects, particularly large objects, from orbit, and attention to this subject is now increasing as a result of its inclusion in the 2010 National Space Policy. Apart from preparing for the future of orbital debris prevention and mitigation, NASA and the U.S. government already have tools to address this issue to some degree.

Panelists discussed the use of tools such as conjunction assessment risk analysis (CARA) to forecast possible collisions between cataloged objects and operational spacecraft. CARA takes information from the Department of Defense's (DOD's) Joint Space Operations Center (JSpOC) and converts it into collision probabilities, which are then sent to the appropriate mission directors, who are ultimately responsible for making decisions on whether to initiate an orbit change for a satellite in potential danger. It was stated that, although this tool works efficiently, it can only be as good as the information entered, since particles smaller than what JSpOC can track can still cause significant damage. A panelist suggested that improving the quality and detail of the data received for CARA was a goal that could be met in part by improvements in how JSpOC screens and cross-checks its ephemeris[3] data before sending it to NASA, as well as by having NASA join the Space Data Association, a non-profit organization of commercial satellite operators established to provide this type of support to industry users.

In addition to tracking and collision analysis efforts, it was noted that greater attention is being given to designing spacecraft for "passivation"[4] so that spacecraft are less likely to create more debris from explosions or if struck by an object. Space systems can also be designed and constructed so that they are less likely to survive to the ground when they enter the atmosphere, thus posing less risk to people on the ground.

Nevertheless, technology and engineering solutions are still subject to administrative pressures. Such issues were brought up by a number of the NASA speakers, but one administrative issue was repeatedly mentioned: budgets are presently set on a year-by-year basis instead of a 2-year basis as in the past. This makes planning very difficult. For example, it was stated that there will likely be cost-overruns on the Meter Class Autonomous Telescope, which may occur late in this fiscal year. This would present the project manager with a challenge: Should they save a reserve and risk losing it on October 1? Or should they spend it all now and risk running out too early? The funding cycle is absolute; after the fiscal year, any remaining funds from what were provided that year disappear.

Another issue brought forward by the NASA leads is that the workforce in this area is not extensive enough to ensure continuity of expertise, nor are there sufficient resources to train new people or hire young engineers. This, too, is essentially a budgetary problem.

Research in the area of meteoroids is prone to many of the same problems as elucidated above, a point emphasized by one speaker who mentioned that approximately 40 percent of MMOD impacts on the space shuttle's surface are from meteoroids. The task for the Meteoroid Environment Office is to identify the "background" meteoroid environment and the occasional meteoroid showers and their characteristics and then provide forecasts of possibly damaging effects in the regions of space outside LEO, where orbital debris does not dominate the hazard.

The NASA speakers expressed the need for research to develop a model of meteoroids in the outer solar system (Jupiter and beyond), improve instrumentation calibration for measuring meteoroid properties and trajectories, and resolve the question of whether spacecraft instrument failures are due to inherent component degradation or to electrical effects caused by impact of meteoroids traveling at velocities up to 70 km/s. The latter subject raised a

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[2] The "25-year rule" is a guideline adopted by the international organization, the Inter-Agency Space Debris Coordination Committee (IADC) in its "IADC Space Debris Mitigation Guidelines" released in 2002 and revised in 2007. The "rule" encourages entities with objects in low-Earth orbit to ensure that their spacecraft and/or launch hardware are in an orbit that will decay and cause said object to reenter Earth's atmosphere within 25 years to mitigate the creation of more orbital debris. See http://www.iadc-online.org/Documents/Docu/IADC_Mitigation_Guidelines_Rev1_Sep07.pdf.

[3] Data that provides the positions of spacecraft and other astronomical objects at a given time.

[4] Passivation is the disabling of a satellite or object in space to prevent that object from creating more orbital debris, such as by exploding in orbit or colliding with another spacecraft. This can be accomplished in many ways, including draining onboard batteries, expending excess propellant, and/or positioning the object for atmospheric reentry.

good deal of commentary, because, until recently, electrical failures were assumed to be caused by either internal effects or space weather and were simply labeled as anomalies. However, one of the panelists described working with hypervelocity and plasma physics experts to investigate electrical anomalies caused by high-velocity meteoroid strikes so as to provide data that will better inform people dealing with this issue.

Recent advances in low-mass and low-power sensors, it was explained, open the possibility of covering large areas of a spacecraft with MMOD impact detection and location systems, which could also provide data for anomalies and failure analysis and perhaps even alerts on debris streams. Moreover, calibrated sensors could provide data on the size and flux of MMOD particles, and multifunctional shielding (combining thermal, radiation, self-healing and MMOD protection functions) could reduce MMOD risk and shielding mass.

At the end of the session, attendees from non-NASA organizations praised the efforts and accomplishments of the NASA MMOD programs, particularly when taking into account the small budgets under which the various entities operate.

SESSION 2: NASA MISSION OPERATORS

Five NASA project and mission managers described specific missions from an operations standpoint, emphasizing the design tools they use to meet MMOD requirements and their experiences with actual MMOD encounters or anomalous effects that may be attributed to such encounters. The missions represented on this panel were the Global Precipitation Measurement (GPM) mission; the ARTEMIS mission, which studies the Earth-Moon environment; the Hubble Space Telescope; the Earth observation missions Jason-1 and Ocean Surface Temperature Mission/Jason-2; and NASA Goddard Space Flight Center's Space Science Mission Operations project, which is responsible for the management of space science missions from conceptual development through end of operations.

Committee members were interested in learning what MMOD-related problems missions encounter throughout the lifetime of a spacecraft, how NASA's MMOD programs meet mission planners' and operators' needs, and what information mission managers are using to make decisions related to the operations of a spacecraft—in particular, those decisions related to MMOD.

The speakers said that Debris Assessment Software (DAS), which is a single modeling tool, is used for determining compliance with MMOD-related design requirements,[5] but a number of speakers indicated that, although the software was easy to use and provided free to the public, it was essentially a "black box." Users do not know how DAS arrives at its outcomes, so the user is unsure whether the results are conservative or not. The Object Reentry Survival Analysis Tool (ORSAT), which is used to predict the reentry survivability of satellite and launch vehicle upper-stage components that are entering due to orbital decay or from controlled entry, was stated to be more accurate than the reentry survivability predictor in DAS. Nevertheless, DAS was given a favorable opinion by panelists when used for its intended purpose.

In addition to demonstrating compliance with MMOD-related design requirements laid out in NASA Technical Standard 8719.14, the GPM program manager highlighted that the GPM mission used DAS to determine the shielding design for the satellite as well, which is not the software's primary purpose. Some panelists expressed a desire for better verified software to assist with shielding design, and one speaker explained that the project team would have liked to have verified the design by using the BUMPER model but could not, primarily because of factors out of the project team's control, namely funding.

Some of the speakers discussed the question of anomalous behavior and whether it could be traced to MMOD effects. Examples were given to illustrate the analysis that must be carried out to explain why a given effect that was initially noted as an instrument response might, for example, lead to conjecture that it could have been due to a meteoroid or orbital debris collision. When the Artemis spacecraft lost functionality of an instrument, the designers concluded that the support structure most likely broke due to fatigue, but the speaker highlighted the difficulty in arriving at a clear reason for the loss of data when first presented with a spacecraft anomaly.

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[5] All NASA missions are required to comply with the NASA Technical Standard 8719.14, "Process for Limiting Orbital Debris," which provides "uniform engineering and technical requirements for processes, procedures, practices, and methods" for NASA projects and programs; available at http://www.hq.nasa.gov/office/codeq/doctree/871914.pdf.

The Hubble Space Telescope presented an interesting case because its development in the 1970-1980 time frame meant that it was not designed to perform any collision avoidance and was constructed with no significant shielding against MMOD impact strikes. As the risk of orbital debris damage increased, the HST team developed an orbit debris conjunction mitigation contingency procedure to handle predicted possible collisions with an object in the tracking catalog. The procedure uses a combination of real-time commanding and flight software macros for configuring HST in the event of a possible conjunction, and myriad contingency actions have been developed as a result. However, no conjunction assessment to date has caused an interruption to HST science operations. In case of a predicted close encounter with orbital debris, HST cannot change orbit but can only orient itself in such a way as to reduce the probability of a collision. The degree of risk involved in such a maneuver, however, needs to be weighed against the potential collision risk. To date, HST has never conducted this type of procedure. HST has furnished a great deal of photographic evidence of meteoroid collisions taken during space shuttle servicing missions, which have helped to build up a catalog of information useful to designers in the future.

The question was asked as to whether there has been any loss of science data or loss of engineering and vehicle performance on HST due to any type of debris. The reply was that most or all of the impacts on HST have been from meteoroids, not orbital debris, and they have not degraded or affected HST operations.

Two other missions represented at the workshop—Jason-1 and Jason-2—are collaborations between NASA, the National Oceanic and Atmospheric Administration (NOAA), and Centre National d'Etudes Spatiales, the French space agency, measuring sea levels, water vapor in the troposphere, and ocean surface temperature, among other scientific measurements. The international partnership necessitates the sharing between the two agencies of information that is protected both by International Traffic in Arms Regulations[6] and a similar set of French export regulations. While the results of calculations on such matters as conjunction assessment numbers could be shared, the methods behind the calculations typically could not be shared, so no critical comparisons between the underlying assumptions in the calculations could be made.

The unintended consequences of compliance with debris regulations were illustrated in the case of the next satellite in this series, tentatively referred to as Jason-3 and/or Jason-CS, which is being designed to carry additional propellant that could be used to decommission or passivate the mission. However, carrying extra propellant would result in an increase in the collision cross section of the satellite, leading to a greater probability of collision and a greater debris risk if the propellant tank ruptures. If the mission fails and cannot be fully decommissioned, a drifting spacecraft with a much larger explosive potential would remain in orbit. Most spacecraft used for science missions, in particular those designed and launched prior to implementation of NASA's current engineering design standards for mitigating creation of orbital debris, typically do not maneuver during their lifetime and lack propulsion systems that would allow them to deorbit for atmospheric reentry or avoid a collision.

SESSION 3: THE ROLE OF NASA'S MMOD PROGRAMS AND THEIR RELATIONSHIP TO OTHER FEDERAL AGENCIES

Representatives from the DOD, Federal Aviation Administration (FAA), NOAA, Department of State, and the Federal Communications Commission (FCC) involved in space policy, space and Earth science, and MMOD issues discussed challenges they face from the space environment, interagency issues and opportunities for collaboration, and how and to what extent they engage NASA's MMOD programs.

One of the panelists noted that at the beginning of 2010, the Space Protection Program, a joint U.S. Air Force Space Command and National Reconnaissance Office program that advises the intelligence and military community on how to protect their critical space assets, conducted a study on orbital debris and concluded that orbital debris was a very significant problem requiring immediate action. The United States, the study concluded, could not wait to develop removal technologies, and an implementation plan was discussed. That plan was never implemented for the following reasons:

- Most of the proposals had a weapons-like character about them;

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[6] International Traffic in Arms Regulations, available at http://www.pmddtc.state.gov/regulations_laws/ itar_official.html.

- No agreement could be reached on who would be responsible within the United States or internationally;
- The cost did not justify moving forward; and
- There was a lack of agreement on policy.

When it came to the point of including a statement in the text of the 2010 National Space Policy on actively removing debris from space, a panelist recalled, that phraseology was removed from the final version and the text now reads only that studies related to removal should be carried out.

One of the panelists made the observation that, in his opinion, if there is going to be any active debris removal in our lifetime, it will be done by commercial organizations. He cited an announcement that Intelsat is having informal talks with NASA about refueling satellites in geosynchronous or geostationary Earth orbit (GEO) for removal, and noted that ViviSat and DLR Germany are also working on this approach. He went on to say that U.S. policy for debris removal will not be developed, written, or changed in our lifetimes unless there is a catastrophic event in space. In the interim, NASA could fund commercial activities that would lead to debris removal, and it could also continue to fund research in this area.

A spokesman for the FAA said his agency is a regulatory agency, and its authority is more limited, in a sense, than NASA's authority. The FAA has the authority to license launches and reentries that are purposeful and designed to survive substantially intact. The only MMOD-related requirement the FAA has is for passivation of upper stages by depleting propellants and drawing down energy sources. He said that his organization receives excellent support from NASA's ODPO. The FCC is also a regulatory agency and derived the baseline for its guidelines for the mitigation of orbital debris from the Inter-Agency Space Debris Coordination Committee (IADC). However, the FCC representative did say that the FCC often sends people seeking commercial licenses from the FCC to NASA's ODPO Web site to conduct their own preliminary assessment there before filing for a license. The FCC representative further bolstered NASA's reputation in the MMOD community by saying that the FCC looks forward to NASA's continued work, because "it's where the FCC goes to."

While NASA has a criterion of a 1×10^{-4} probability of risk for casualties on reentry, the FAA has a requirement of a 30×10^{-6} probability of ground damage from debris for just a launch, or for launch and controlled reentry combined, thereby underscoring differences in handling MMOD across agencies. This is one of many differences that illustrates the varied MMOD governmental policies in place that are not always coordinated across agencies, a fact that did not go unnoticed at the workshop. The FAA does not follow the 25-year rule, because it has not done a cost-benefit analysis to support its implementation. In order for the FAA to justify new policies or regulations, the agency representative explained, any new policies or regulations would have to decrease the cost of a casualty 10-fold based on the FAA's current reentry damage/casualty probability threshold. The FCC, on the other hand, does follow the 25-year rule end-of-life guideline, but the FCC representative also noted that the issue of debris mitigation is not at the forefront of the organization's planning apparatus.

A representative of the State Department discussed international efforts to mitigate the effects of orbital debris. The most prominent international body for information exchange on space debris is the 11-nation IADC. Since 1993, the IADC has conducted annual meetings to discuss research results in the areas of measurements, modeling, protection, and mitigation. The IADC is internationally recognized as a space debris center of competence and influences space debris mitigation activities through the United Nations (UN) Committee on the Peaceful Uses of Outer Space–Scientific and Technical Subcommittee.

As the State Department looks over the horizon, it sees an increasing number of governmental and non-governmental actors operating in space. The State Department is compelled to ensure that all groups conduct themselves responsibly in space, but the optimal approach remains elusive for now. The State Department is looking at what are some minimal actions nations can take to mitigate the creation of orbital debris, as well as reduce the risk to space assets from natural and manmade debris already in orbit. International avenues for addressing MMOD issues are adequate up to a point, but international guidelines are non-binding, and there is no supranational adjudicative body tasked specifically with international space law. The prime challenge in the future will be translating international consensus and standards into action on the national stage for individual countries. Although the majority of the world's nations are signatories to treaties like the UN Outer Space Treaty and UN Liability Convention, there remain some that have yet to sign. This problem is compounded by countries, including treaty signatories like Brazil and India, that acknowledge the need for a sustainable space environment but do not want their space programs impeded by guidelines developed by the nations that created the problem of space debris in the first place—namely Russia (and former Soviet Union) and the United States.

The panel speakers all asserted that they derive tremendous value from NASA's ODPO, which also allows their agencies to speak knowledgeably about MMOD issues in international and interagency forums. In the case of NOAA, NASA builds the spacecraft and treats them as they would a NASA mission. Nonetheless, the relationships between these agencies and NASA's MMOD programs vary from agency to agency, and it was revealed at the workshop that there were varying degrees of coordination on the matter within the agencies themselves. When asked who the technical lead is within DOD on MMOD issues, the DOD panelist said that there was no such position at DOD, an agency with an even larger space portfolio than all of the U.S. government's civil space programs combined. When this question was asked for the entire U.S. government, the panelists said that there is no true lead for MMOD in the U.S. government as a whole either.

Responding to a question about data sharing and spacecraft anomaly analysis and cataloging, panelists explained how interagency data either are not shared or are heavily edited before going from classified to non-classified status, and that the commercial industry is not a particularly helpful or reliable source of anomaly information.

SESSION 4: MMOD AND THE COMMERCIAL INDUSTRY PERSPECTIVE

Representatives of the satellite communications firm Iridium Satellite Communications, aerospace manufacturer Lockheed Martin, and insurance firm XL Insurance talked about how MMOD affects business operations, from the manufacturing of spacecraft to making on-orbit decisions about possible collisions. Among many other topics, this panel discussed the tools industry uses to make decisions affecting their space assets, what their relationship is with NASA's MMOD programs, and what opportunities for collaboration there might be between industry and NASA.

After hearing from various NASA employees and other federal agency representatives, the panel provided a different perspective on the MMOD issue, starting with a description of the Iridium firm and the 2009 collision event between Iridium 33 and the Russian satellite Cosmos 2251. In the past, explained the Iridium representative, there was never any information on orbital characteristics that could be relied on for actionable decisions by program/mission managers, including two-line elements.[7] Up until 2009, in fact, Iridium had never adjusted a satellite's orbit, and the predominant attitude toward spacecraft and orbital slots was the "Big Sky"[8] viewpoint. A review of predicted conjunctions for February 10, 2009, showed a possible collision between the Iridium 33 and Cosmos 2251 satellites, but that conflict was 16th on a list of possible conjunctions, so no action was taken.

The Iridium 33-Cosmos 2251 conjunction was the first payload-to-payload collision in the history of spaceflight. Following the collision, Iridium initiated an anomaly recovery process, coordinating with JSpOC throughout this process. As a result, the company has a more robust relationship with JSpOC, but the Iridium representative did not mention involvement from NASA's ODPO. When asked if a more careful analysis of conjunction using all of the data available would have predicted the collision, the Iridium representative said that the company is in the midst of conducting an analysis, and a report will be published with those results.

Today, Iridium receives daily conjunction assessment updates from JSpOC, which are assessed to gauge the level of risk for each reported conjunction. Since the 2009 conjunction event, Iridium has made 41 maneuvers, whereas before 2009 it had made none.

Although Iridium has not interfaced a great deal with NASA or NASA's ODPO, the representative from Lockheed Martin explained how that company incorporated NASA's work in MMOD into the design and construction of NASA's Orion crew vehicle capsule. Orion is the first human-rated reentry spacecraft designed to stringent

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[7] A *two-line element* is a set of two 69-character lines of data used to describe the orbit and perturbations of a satellite around Earth. New two-line element sets are generated by the Air Force Space Command on an as-needed basis and not according to a previously established timetable.

[8] According to "Big Sky" proponents, the number of spacecraft in Earth orbit is negligible, given the overall scale of the environment being considered.

MMOD-related design requirements for a variety of missions, including to LEO, the Moon, and Mars. Engineers make difficult decisions when designing spacecraft shields, since there are always tradeoffs to increasing shielding, such as increased cost, volume, and mass to the spacecraft (for mechanical, not electrical, shielding). The increase of orbital debris in the space environment only makes this task harder. The speaker identified two levels of concern in designing Orion: (1) loss of crew, which includes damage to the Orion vehicle either in orbit or during reentry, and (2) loss of mission, which includes damage that prompts a mission abort or an unsafe vehicle reentry. The project team used the BUMPER II code to analyze more than 500 shield configurations, which will allow Orion to stay in orbit for roughly 6 months. In addition, NASA's Orbital Debris Environment Model (ORDEM) and Meteoroid Environment Model (MEM) were combined with Orion attitudes and trajectories for calculating a variety of design-related needs based on mission scenarios. Finally, the design team performed shield tests at facilities such as the University of Dayton Research Institute and White Sands Test Facility. These facilities can launch particles at between approximately 6.5 km/s and 10 km/s, but, as some committee members pointed out, these speeds are still below the maximum relative impact velocities for debris in LEO and lower by a factor of 2 to 10 than the speed of all meteoroid populations. The result of these tests and analyses is an MMOD shielding mass that is a little more than 0.5 percent of the total vehicle mass.

The representative of Lockheed Martin also discussed launch vehicles, saying that there are no requirements for launch vehicle de-orbiting of spent stages. However, in the case of a transfer orbit GEO, a launch company can decay the orbit of the spent stage so that atmospheric drag will eventually cause reentry of the rocket. In addition, efforts are made to ensure that propellant tanks are emptied and depressurized after launch.

The potential for further debris creation, perhaps by a spent rocket stage that has not de-orbited yet, relates directly to another area covered by this panel: space insurance. The XL Insurance representative described the state of the space insurance industry as having events that are low in frequency but very high in severity. This issue is compounded by the fact that the space insurance industry does not have a very large funding reservoir. Space insurance covers first-party losses (e.g., loss of asset, loss of revenue) and third-party losses (e.g., liability for damage to third parties) of satellite operators, launch providers, satellite and launch vehicle manufacturers, and others. There are currently 195 insured satellites in orbit for a total insured value of $19.8 billion. Over the past decade, the probability of satellite failure after completion of orbit raising and initial testing, as assumed by the insurance industry, oscillated between 1.5 and 2.0 percent per year. The speaker also noted that MMOD damage is covered by typical space insurance packages.

Third-party insurance claims for objects in space can be complicated by the vagaries of international space law. Determining the cause of an incident and subsequent liability can be very difficult. According to the UN Liability Convention of 1972,[9] the launching state is liable for objects in space that were launched from within its borders. Determining the cause of an incident and subsequent liability, however, can be very difficult. According to the UN Liability Convention of 1972, a launching state can be liable for its own launches or launches it procures that occur from its own territory or facilities. Fault is the standard that applies to damage that occurs in space. Determining fault requires proving that the launching state's conduct violated an applicable standard of care. The treaty regime also makes it illegal for a nation to unilaterally remove an object or derelict spacecraft from orbit if it is not also the launching state. In the case of the Iridium-Cosmos collision, there was no clear onus of responsibility for maneuvering either satellite.

When panelists were asked to suggest areas in which NASA could provide augmented or additional services, one panelist expressed a desire for more and "better" data on the outer solar system environment and more high-velocity shield testing. Another panelist wanted more effort made to enhance the ability to track satellites in orbit, including greater cooperation between NASA and JSpOC. The idea of using hosted payload slots to launch missions to characterize the MMOD environment was brought forward as well. Finally, a panelist said that ODPO's quarterly newsletter is very useful, but that he would like to see the charts used in the newsletter updated more frequently, as well as for NASA to provide greater access to more regularly updated data elsewhere. After hearing

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[9] Convention on International Liability for Damage Caused by Space Objects, available at http://www.oosa.unvienna.org/oosa/SpaceLaw/liability.html.

this comment, a NASA employee told the gentleman to get in touch with him, and he would provide the panelist with whatever information he needed.

SESSION 5: ORBITAL DEBRIS RETRIEVAL AND REMOVAL

The 2010 National Space Policy calls for NASA and DOD to lead research and development efforts in orbital debris retrieval and removal. Representatives of NASA's technology development programs, DOD, and the Office of Science and Technology Policy (OSTP)[10] talked about these efforts and what it would take to help engineer a safer space environment.

Space policies convey themes and opportunities to external organizations, as well as provide guidance to government agencies. There have been national space policies in the United States since the Eisenhower Administration, and, according to the OSTP representative, the UN Outer Space Treaty will continue to be a foundation for U.S. space policies.

The 2010 National Space Policy places significant new emphasis on broad international cooperation with the goal of increasing stability and transparency in space. Preserving and ensuring a sustainable space environment is necessarily an international endeavor, and there will only be more national and non-governmental actors in space over the coming years and decades.

The new space policy, explained the OSTP representative, tries to address orbital debris in multiple ways to strengthen measures to minimize creation of debris; call for agencies to continue to lead in the development and adoption of standards; improve data sharing, both among agencies and internationally; and encourage agencies to utilize tools already in their arsenal to mitigate and possibly remove orbital debris. Some examples include finding synergies between U.S. Strategic Command and NASA models, data collection, and conjunction analyses. Emphasis is placed on research and development because the government does not yet know what technologies will ultimately be necessary or are feasible on the scale required for effective orbital debris retrieval and removal, as well as guaranteed prevention of collisions if such an event is predicted. Although the National Space Policy calls for research and development in this field, it does not specify a threshold or goal, but rather intends such research and development as a beginning to the entire process.

The recently created NASA Office of the Chief Technologist (OCT) plans to work on new "game-changing" technologies across many disciplines, including orbital debris retrieval and removal. Among the new division's many goals, OCT will be the principal NASA advisor and advocate on matters concerning agency-wide technology policy and programs, direct management of OCT Space Technology Programs, and coordination of technology investments across the agency. OCT will work on technologies from technology readiness levels (TRLs) 1-7, divided into three groups: early-stage innovation (TRL 1-2), game-changing technology (TRL 3-4), and crosscutting capability demonstration (TRL 5-7).

Regarding orbital debris, OCT will participate in studies of the problem and partner with others to develop technologies that allow for orbital debris hazard mitigation and removal, including releasing solicitations for orbital debris-related technologies that have specific parameters. NASA's ODPO will be the focal point for these activities and, among its other responsibilities, will remain in charge of environment characterization, while OCT focuses on the development of new technologies. In formulating its solicitations, OCT is using responses from requests for information and is conducting discussions with mission directorates, the Orbital Debris Program Office, and industry.

The OCT representative also considered the idea of a U.S. government interagency study to address the issue of orbital debris. None of NASA's mission directorates have taken responsibility for addressing orbital debris, even though the 2010 National Space Policy tasks NASA with taking a lead. When asked how such a study might proceed, panelists replied that there are a variety of ways a study could be convened. The process could begin

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[10] The Office of Science and Technology Policy, an executive branch-level office, is the lead office for providing the president of the United States with scientific and technical advice, as well as coordinating presidential science and technology policy throughout the U.S. government.

in a number of ways, including in the executive branch, at the agency level, or in an informal setting between government employees.

Despite an acknowledgment from NASA and OSTP that MMOD is a major issue that needs to be addressed, an even more immediate concern voiced by a senior NASA official was the agency's budget, echoing earlier statements made by the Session 1 panelists. Not only is the amount of funding available for the agency a source of anxiety, but so too is the uncertainty of that funding under a series of continuing resolutions instead of a true appropriations bill. One panelist said that he has not yet seen a credible amount of funding for implementation or research into characterizing or improving the space environment.

Nevertheless, NASA will continue to consider MMOD concerns for exploration technologies, and agency-level requirements to reduce crew risk is a driver for spacecraft design. Right now, the International Space Station is the benchmark for safety and protection from MMOD, but NASA wants to expand beyond it. Members of this panel noted that another area that needs improvement is information and data sharing across agencies and international lines.

When asked what some of the obstacles are to sharing MMOD-related data, an issue that was prevalent throughout the workshop, panelists suggested numerous reasons. One panelist explained how there is a tendency toward mission-specific solutions; a mission can be a driver for data sharing, but data sharing in and of itself is not necessarily useful. Another panelist said that figuring out the objective of data sharing is just as important as what is being shared, and who is involved is a challenge all of its own. Perhaps the greatest obstacle, though, is time. Gathering everyone involved to work out solutions is very time consuming, and there is no shortage of other pressing government challenges that all require serious attention. At the end of the session, some panelists noted that they were still not sure what are the greatest risks posed by debris, nor was it clear whether there has been a comprehensive risk assessment conducted about MMOD on a global scale.

OBSERVATIONS OF INDIVIDUAL COMMITTEE MEMBERS

The following observations were made by committee members following the workshop presentations in closed session and were then communicated to the audience and panelists within the hour, constituting the concluding portion of the workshop. As stated during the workshop, they should not be interpreted as findings or recommendations of the committee nor committee consensus, but rather, as the title suggests, observations from individual committee members following the workshop presentations and the subsequent discussions with the panelists and members of the audience.

- The committee heard that one of the NASA MMOD programs' goals, if not the overriding goal, is to protect the space environment.
- The NASA MMOD programs have well characterized the threat posed by orbital debris and have influenced the space community and industry to take MMOD considerations into greater account in spacecraft designs and human spaceflight operations.
- There is uncertainty surrounding how to move forward with active removal of debris, and there does not appear to be an economic basis for orbital debris retrieval or removal. There seems to be a gap between policy and the capability to implement the policy.
- It remains unclear if a probabilistic risk assessment has been conducted that would help provide overall guidance for the programs, but such an assessment might be a useful activity.
- There are still some areas in which agencies working on MMOD issues are trying to structure a stronger regulatory framework, and this ongoing process should bear some fruit in coming years.
- U.S. foreign policy likes to set examples for other nations as a way of encouraging them to adopt procedures or guidelines that the United States believes are good and appropriate. There seems to be a fractured understanding across U.S. agencies as to their adoption, use, and clarifications of the MMOD guidelines, which became clearer throughout the workshop. If this improved understanding is further refined, the United States could provide a clearer example for other countries of how to structure similar governmental MMOD programs.
- The number and the variety of users of NASA MMOD programs, data, models, and services are impressive, with most of these interactions being carried out without formal contracts, compensation, or acknowledgment.

- If NASA moves forward with actual orbital debris retrieval, it will be a tremendous, time-intensive project.
- A lot of research needs to be done to improve the quality of conjunction assessment models.
- Conjunction analysis has gained greater prominence in the space community, and its use has increased over recent years. Nevertheless, despite U.S. Air Force efforts to provide more data to government agencies and industry on this matter, release of data appears inconsistent and infrequent, according to what was heard at the workshop.
- Engineering models like ORDEM2000 and BUMPER continue to be improved. If NASA could update publicly available models more frequently, the space community would benefit greatly in designing its own spacecraft with the most up-to-date information.
- The large differences between rules among the different agencies to satisfy MMOD guidelines are surprising.
- The fact that the 2010 National Space Policy focuses on the issues associated with orbital debris and is on target is impressive, despite the paucity of technical input in the policy formulation phase.
- Funding and personnel issues pose great challenges to NASA's MMOD activities.
- Numerous national, international, and commercial entities have extensive spacecraft anomaly databases, yet, based on what was heard at the workshop, efforts to consolidate or summarize the data have been ineffective.
- Not having a single point of contact within NASA with authority over all MMOD program elements, modeling, and tool development appears to undermine ensuring the flexibility, consistency, quality, and relevance of priorities set across NASA.

REPRINTED WORKSHOP REPORT

Appendixes

REPRINTED WORKSHOP REPORT

A

Letter of Request

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

April 26, 2010

Reply to Attn of: Office of Safety and Mission Assurance

Dr. Raymond A. Colladay
Chair, Aeronautics and Space Engineering Board
National Research Council
500 5th Street, NW
Washington, DC 20001

Dear Dr. Colladay:

The White House Office of Management and Budget and Office of Science and Technology Policy have requested that the NASA Administrator "establish a National Research Council [NRC] study of opportunities for NASA to enhance the benefits delivered by its orbital debris program in the context of a fairly constrained budget environment."

For the past two decades, NASA has built a robust program to evaluate and limit the generation of orbital debris (OD) and the risk to NASA spacecraft associated with OD and micrometeoroids (MM). NASA's OD and MM programs are recognized worldwide, yet with the growth of orbital debris over the past few years, we recognize the responsibility to use our capabilities and assets to support not just NASA needs, but also to support, as a national resource, other national and international OD and MM activities. The NRC generated foundational studies of these issues in 1989, 1995, and 1997, all of which form the basis for NASA's role in OD and MM. Therefore, we request that the NRC conduct a study to:

- Review existing NASA policy/efforts and organization with regards to OD and MM, including:
    - Modeling and simulation
    - Detection and monitoring
    - Protection
    - Mitigation
    - Reentry
    - Collision Assessment Risk Analysis and Launch Collision Avoidance
    - Interagency cooperation
    - International cooperation
    - Cooperation with the commercial space industry
- Assess whether NASA should initiate work in any new OD/MM areas.
- Recommend whether NASA should increase or decrease effort, or change the focus of, any of its current MM/OD efforts (within a fairly constrained budget) to improve the office's ability to serve NASA and other national and international activities.

I would like to request that NRC submit a plan to NASA for this study. NASA will provide a review of current OD and MM efforts and associated data sources to NRC at an early opportunity. The results of this study will be of the highest value to NASA in formulating the FY-2013 budget. We will need the findings and recommendations review completed by March 31, 2011. Once agreement with NRC on the scope and cost of the proposed study has been achieved, the NASA Contracting Officer will issue a task order for implementation. Mr. John W. Lyver, IV, will be the NASA technical point of contact for this effort and may be reached at (202) 358-1155 or by e-mail at JLyver@NASA.GOV.

Sincerely,

Bryan O'Connor

Bryan O'Connor
Chief, Safety and Mission Assurance

B

Statement of Task

The National Research Council, under the auspices of the Aeronautics and Space Engineering Board, will establish an ad hoc committee to assess NASA's orbital debris programs and provide recommendations on potential opportunities for enhancing their benefit to the nation's space program.

The committee will:

1. Review NASA's existing efforts, policies, and organization with regard to orbital debris and micrometeoroids, including efforts in the following areas:

   - Modeling and simulation;
   - Detection and monitoring;
   - Protection;
   - Mitigation;
   - Reentry;
   - Collision assessment risk analysis and launch collision avoidance;
   - Interagency cooperation;
   - International cooperation;
   - Cooperation with the commercial space industry.

2. Assess whether NASA should initiate work in any new orbital debris or micrometeoroid areas.
3. Recommend whether NASA should increase or decrease effort in, or change the focus of, any of its current orbital debris or micrometeoroid efforts to improve the programs' abilities to serve NASA and other national and international activities.

The committee should assume that the programs will be operating in a constrained budget environment.

The study will result in two reports. The first will be a workshop report and the second will be the committee's final report at the conclusion of the study.

This project is sponsored by NASA.

C

Workshop Agenda

MARCH 9, 2011

10:30 a.m. Workshop Introduction Don Kessler, *Chair*

10:35 a.m. **Session 1: NASA Meteoroid and Orbital Debris Programs**

The leads for NASA's Meteoroid and Orbital Debris (MMOD) programs will speak about program goals, issues, gaps, and opportunities.

Panelists:
John Lyver, Office of Safety and Mission Assurance, NASA Headquarters, Manager of NASA's Meteoroid and Orbital Debris Program Offices
Gene Stansbery, NASA Orbital Debris Program Office, Johnson Space Center
William Cooke, Meteoroid Environment Office, Marshall Space Flight Center
Eric Christiansen, Hypervelocity Impact Technology Group, Johnson Space Center/Human Exploration Science Office
Lauri Newman, NASA Robotic Conjunction Assessment Risk Analysis, Goddard Space Flight Center

12:00 p.m. Lunch

12:45 p.m. **Session 2: NASA Mission Operators**

Project managers and system engineers from various NASA robotic missions will discuss MMOD issues from an operations standpoint. What MMOD-related problems do missions encounter throughout the lifetime of a spacecraft? How do NASA's MMOD programs meet mission planners' and operators' needs? What information are mission managers using to make decisions related to the operations of a spacecraft, and how do mission managers make MMOD-related decisions?

Panelists:
Michael Rhee, Systems Engineer, Global Precipitation Measurement Mission, Goddard Space Flight Center

Mark Woodard, Senior Flight Dynamics Engineer, ARTEMIS Mission, Goddard Space Flight Center
Patrick Crouse, Operations Project Manager, Hubble Space Telescope, Goddard Space Flight Center
Glenn Shirtliffe, Project Manager, Jason-1 and OSTM/Jason-2 Missions, Jet Propulsion Laboratory
Richard Burns, Program Manager, Space Science Mission Operations, Goddard Space Flight Center

2:15 p.m. **Session 3: Role of NASA's MMOD Programs and Their Relationship to Other Federal Agencies**

Representatives of U.S. government agencies involved in space policy, space and Earth science, and MMOD issues will discuss challenges they face from the space environment, interagency issues and opportunities for collaboration, and how and to what extent they engage NASA's MMOD programs.

Panelists: Andrew Palowitch, Director, Space Protection Program, Air Force Space Command/National Reconnaissance Office
Phil Brinkman, Program Lead for Licenses, Office of Commercial Space Transportation, Federal Aviation Administration
Mark Mulholland, Senior Advisor, Office of Systems Development, National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration
Kenneth Hodgkins, Director, Space and Advanced Technology, Bureau of Oceans and International Environmental and Scientific Affairs, U.S. Department of State
Karl Kensinger, Associate Division Chief, Satellite Division, International Bureau, Federal Communications Commission

4:15 p.m. Day 1 Adjourns

6:00 p.m. Committee Working Dinner

MARCH 10, 2011

9:00 a.m. **Session 4: MMOD and the Commercial Industry Perspective**

Members of the aerospace and space insurance industries will talk about how MMOD affects business operations, from the manufacturing of spacecraft to making on-orbit decisions about a possible collision. What tools does industry use to make decisions affecting their space assets, what is industry's relationship with NASA's MMOD programs, and what opportunities for collaboration are there between industry and NASA?

Panelists: John Campbell, Lt. Gen. (ret.), USAF, Executive Vice President of Government Programs, Iridium Satellite Communications
Larry Price, Orion Deputy Program Manager, Lockheed Martin Space Systems
Chris Kunstadter, Senior Vice President, XL Insurance

10:45 a.m. **Session 5: Panel on Orbital Debris Retrieval and Removal**

The 2010 National Space Policy calls for U.S. government research and development efforts to be made to retrieve and remove orbital debris, but how will that policy be turned into action?

Representatives of NASA's technology development programs, the Department of Defense, and the Executive Office of the President will talk about these efforts and what it will take to help engineer a safer space environment.

Panelists: Wilson Harkins, Deputy Chief, Safety Mission Assurance, NASA
Steven Meier, Director, Crosscutting Capability Demonstration Division, NASA Office of the Chief Technologist
Damon Wells, Senior Advisor, Office of Science and Technology Policy

12:30 p.m. Lunch and Committee Working Lunch in Closed Session

1:30 p.m. Discussion of Observations and Conclusions from Workshop

2:00 p.m. Workshop Adjourns

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Committee and Staff Biographical Information

COMMITTEE FOR THE ASSESSMENT OF NASA'S ORBITAL DEBRIS PROGRAMS

DONALD J. KESSLER, *Chair,* retired from NASA as a senior scientist for orbital debris research. He has more than 30 years of experience in scientific research associated with orbital debris, meteoroids, and interplanetary dust, especially in relation to developing mathematical models, deriving collision probabilities, using sampling techniques, and defining the space environment. Mr. Kessler was a consultant to NASA through Lockheed on orbital debris models and to Prairie View A&M University on orbital debris course development. He worked at NASA's Johnson Space Center as a senior scientist for orbital debris research in the Solar System Exploration Division, where he coordinated NASA's orbital debris research program. He also participated in national and international reviews of other agencies' orbital debris programs and participated in establishing the Inter-Agency Space Debris Coordination Committee, an international agency to address orbital debris issues. He also developed orbital debris models; recommended and developed experiments to test models; analyzed orbital debris data; conducted classes, workshops, and symposia on orbital debris; and recommended cost-effective techniques to control orbital debris. Mr. Kessler modeled interplanetary meteoroid environments, flight control of Skylab experiments, and atmospheric environments, and he developed early orbital debris models and began establishing the need for an orbital debris program. Mr. Kessler participated in U.S. Air Force (USAF) and Strategic Defense Command tests and measurements programs, as well as in studies on orbital debris by various organizations, such as the USAF Scientific Advisory Board, AIAA, the Office of Technology Assessment (OTA), and the Government Accountability Office. Mr. Kessler has published approximately 100 technical articles or extended abstracts on meteoroids and orbital debris and is a contributing author or editor of 10 major reports. He was the managing editor for *Space Debris,* an international journal. He received the IAASS Jerome Lederer Space Safety Pioneer Award, the AIAA Losey Atmospheric Sciences Award in 2000, and the NASA Medal for Exceptional Scientific Achievement. Mr. Kessler received his B.S. in physics from the University of Houston.

GEORGE J. GLEGHORN, *Vice Chair,* is an independent consultant who retired as vice president and chief engineer of TRW Space and Technology Group, now a part of Northrop Grumman. During his 37 years at TRW, he contributed to a wide range of distinguished spacecraft: Pioneer I, the first NASA spacecraft; Pioneer 5, which reported the first data received from interplanetary space; Intelsat III, the first satellite to broadcast live television worldwide; the Orbiting Geophysical Observatory; and NASA's Tracking and Data Relay Satellite. He contributed to Pioneer 6, Pioneer 10, and Pioneer 11 and to the development of the Atlas, Thor, and Titan ballistic missiles.

Prior to TRW, Dr. Gleghorn worked at Hughes Aircraft and at the Jet Propulsion Laboratory, and he served as a naval officer in the Korean War. He is a member of the NAE, a fellow of AIAA, and a member of the Institute of Electrical and Electronics Engineers (IEEE). He has also been a member of independent design and readiness review groups on the Hubble Space Telescope refurbishment mission, the Cassini/Huygens orbiter, the probe of Titan, and the Chandra X-Ray telescope spacecraft. Dr. Gleghorn holds a B.S. in electrical engineering from the University of Colorado and M.S. and Ph.D. degrees in electrical engineering and mathematics from the California Institute of Technology. He was a member of the NASA Aerospace Safety Advisory Panel for 10 years and the NRC National Weather Service Modernization Committee, the Committee on Membership, the Aerospace Engineering Peer Committee, the Committee on International Space Station Meteoroid/Debris Risk Management, and the Committee on Space Debris.

KYLE T. ALFRIEND is the TEES Distinguished Research Chair and Professor in the Department of Aerospace Engineering at Texas A&M University. His areas of research include astrodynamics, satellite altitude dynamics and control, space debris, space surveillance, and space systems engineering. Dr. Alfriend has received the American Association for the Advancement of Science (AAAS) International Scientific Cooperation Award, the AIAA Mechanics and Control of Flight Award, and the American Astronautical Society Dirk Brouwer Award. He is a member of the NAE and a fellow of AIAA. Dr. Alfriend earned his M.S. in applied mechanics from Stanford University and his Ph.D. in engineering mechanics from Virginia Tech. He has served as a member of the NRC's Aeronautics and Space Engineering Board and of the Committee on the Future of the U.S. Aerospace Infrastructure and Aerospace Engineering Disciplines to Meet the Needs of the Air Force and the Department of Defense.

MICHAEL J. BLOOMFIELD is vice president and general manager of space systems at Oceaneering Space Systems. Prior to joining Oceaneering, he was vice president for Houston operations at Alliant Techsystems Inc. (ATK). Mr. Bloomfield is a veteran astronaut of three space shuttle flights. Selected as a NASA astronaut in 1994, he served as pilot on STS-86 and STS-97 and as commander of STS-110. While at NASA he also held important management positions with the astronaut office, including chief instructor astronaut, chief of astronaut safety, and deputy director of flight crew operations. Additionally, Mr. Bloomfield was director of shuttle operations and chief of the shuttle branch. He also served as deputy director of the Flight Crew Operations Directorate before leaving NASA in 2007 to join ATK. Mr. Bloomfield received his B.S. in mechanical engineering from the U.S. Air Force Academy and his M.S. in engineering management from Old Dominion University.

PETER BROWN is a professor at the University of Western Ontario (UWO) and a member of the Western Meteor Physics Group. He studies small bodies of the solar system, with a particular emphasis on meteors, meteorites, meteoroids, and asteroids. His research interests include answering basic questions about the origin and evolution of small bodies in the solar system, such as the origin of meteoroids (comets/asteroids/interstellar and the proportions of each), the origin of meteorites, the physical structure of meteoroids (bulk density/dustballs and what this says about their origin), and the flux and interaction of larger meteoroids at Earth (meteorites, breakup in the atmosphere). Dr. Brown has received the UWO Governor General's Gold Medal and the Plaskett Medal of the Canadian Astronomical Society and the Royal Astronomical Society of Canada, is the Canada Research Chair in Meteor Science, and won an Ontario Distinguished Researcher Award. He earned his B.Sc. in honors physics from the University of Alberta and his M.Sc. and Ph.D. in physics from the UWO.

RAMON L. CHASE is an associate at Booz Allen Hamilton. He has worked on three new concept efforts: the Fly back Booster System, the Point-to-Point Delivery System, and the Transatmospheric Vehicle. He is also the DARPA representative to the Joint NASA DARPA Horizontal Launch Initiative study advisory group. Previously, he was a principal and division manager at ANSER, where he participated in the development of a National Hypersonic Roadmap and an Air Force Integrated Space Architecture. He has served as a study leader at General Research Corporation and as a propulsion lead to the Jupiter Orbiter Planetary Spacecraft Preliminary Design Team at California Institute of Technology's Jet Propulsion Laboratory. Mr. Chase has written more than 30 technical papers on advanced space transportation systems, military space planes, single stage-to-orbit launch vehicles, orbital transfer vehicles, technology readiness assessment, and advanced propulsion systems. He is an AIAA associate fellow and has served on the AIAA Hypersonics Program Committee and the AIAA Space Transportation Technical Committee. He also chaired the Society of Automotive Engineers (SAE) Hypersonic Committee and SAE Space Transportation Committee. Mr. Chase received an M.A. in public administration from the University of California.

SIGRID CLOSE is an assistant professor in the department of aeronautics and astronautics at Stanford University. Prior to joining Stanford, Dr. Close was a project leader at Los Alamos National Laboratory and a technical staff member at the Massachusetts Institute of Technology's (MIT's) Lincoln Laboratory, where she led programs to characterize meteoroids and meteoroid plasma using high-power radars. She was also the lead space physicist for spacecraft monitoring and unplanned space surveillance events and was a project leader for characterizing and modeling ionospheric plasma instabilities. Dr. Close's current research area is in space weather and satellite systems, which includes characterizing and mitigating environmental risks to spacecraft; detecting and characterizing interstellar dust; signal processing and monitoring using radio-frequency satellite systems; and plasma modeling for remote sensing. Her honors and awards include the Joe D. Marshall Award, given by the Air Force Technical Applications Center for Outstanding Technical Briefing, MIT Lincoln Scholar, and first place in the student paper competition at the International Union of Radio Science. She was the vice chair of Commission G of the International Union of Radio Science. Dr. Close received her Ph.D. in astronomy (space physics) from Boston University.

JOANNE IRENE GABRYNOWICZ is director of the National Center for Remote Sensing, Air, and Space Law at the University of Mississippi; and editor-in-chief of the *Journal of Space Law*. Dr. Gabrynowicz teaches space law and remote sensing law and was a founding faculty member of the University of North Dakota Space Studies Department. She has served as the dean of the NASA Space Academy at Goddard Space Flight Center, as the managing attorney of a law firm, and as an official observer for the International Astronautical Federation to the United Nations' Committee on the Peaceful Uses of Outer Space. She was a member of the International Institute of Space Law delegation to the Unidroit Committee of Governmental Experts for the Preparation of a Draft Protocol to the Convention on International Interests in Mobile Equipment on Matters Specific to Space Assets. Dr. Gabrynowicz is the organizer and chair of the Federal Advisory Committee for the National Satellite Land Remote Sensing Data Archive, and she served as a member of the OTA's Earth Observations Advisory Panel and the Department of Commerce Advisory Committee on Commercial Remote Sensing. She advised the Eisenhower Institute on its study "The Future of Space—the Next Strategic Frontier." She is a member of the International Society for Photogrammetry and Remote Sensing International Policy Advisory Committee, the American Bar Association, the Forum on Aviation and Space Law, the New York State Bar, the International Institute of Space Law, and Women in Aerospace, among other groups. Dr. Gabrynowicz received her B.A. from Hunter College and her J.D. from the Yeshiva University Cardozo School of Law.

ROGER E. KASPERSON is a research professor and distinguished scientist at Clark University. He also taught at the University of Connecticut and Michigan State University. He has written widely on issues connected with risk analysis, risk communication, global environmental change, risk and ethics, and environmental policy. Dr. Kasperson has been a consultant or advisor to numerous public and private agencies on energy and environmental issues and served on various committees of the NRC and the Council of the Society for Risk Analysis. He chaired the International Geographical Union Commission on Critical Situations/Regions in Environmental Change. He was vice president for Academic Affairs at Clark University and was elected director of the Stockholm Environment Institute. He served as co-chair of the scientific advisory committee of the Potsdam Institute for Climate Change and is on the Scientific Steering Committee of the START Programme of the International Geosphere-Biosphere Programme. Dr. Kasperson is a member of the NAS and the American Academy of Arts and Sciences. He has been honored by the Association of American Geographers for his research on hazards and is a recipient of the Distinguished Achievement Award of the Society for Risk Analysis. He received his Ph.D. from the University of Chicago.

T.S. KELSO is currently a senior research astrodynamicist for the Center for Space Standards and Innovation (CSSI) in Colorado Springs, Colorado. He has nearly 30 years of experience in space education, research, analysis, acquisition, development, operations, and consulting with organizations such as the Air Force Space Command Space Analysis Center; NASA's Near-Earth Object Science Definition Team; the Air Force Chief of Staff's SPACECAST 2020 and Air Force 2025 future studies; and the Air Force Satellite Control Network. Dr. Kelso has taught on the faculty at the Air War College; the Air Command and Staff College; the Airpower Research Institute; the College of Aerospace Doctrine, Research, and Education; and the Air Force Institute of Technology. He has supported the space surveillance community by operating electronic data dissemination systems to provide the North American Aerospace Defense Command two-line orbital element sets, associated orbital models, documentation, software, and educational materials to users around the world. Dr. Kelso received a B.S. in both physics and mathematics from the U.S. Air Force Academy, an M.B.A. in quantitative methods from the University of Missouri, Columbia, an M.S. in space operations from the Air Force Institute of Technology, and a Ph.D. in mechanical engineering (operations research) from the University of Texas, Austin.

MOLLY K. MACAULEY is a senior fellow and research director at Resources for the Future, where her research has included studies on economics and policy issues of outer space, the valuation of non-priced space resources, the design of incentive arrangements to improve the use of space resources, and the appropriate relationship between public and private endeavors in space research, development, and the commercial enterprise. Dr. Macauley has also served as a visiting professor in the Department of Economics at Johns Hopkins University. She was elected to the International Academy of Astronautics and was selected as a "Rising Star" by the National Space Society. She is on the board of trustees of the National Center for Atmospheric Research and on the board of directors of the American Astronautical Society and the Thomas Jefferson Public Policy Program of the College of William and Mary. She has testified frequently before Congress and serves on many national-level committees and panels. Dr. Macauley earned her B.A. in economics from the College of William and Mary and her M.S. and Ph.D. in economics from Johns Hopkins University. She is a member of the NRC's Space Studies Board and has previously served on the NRC's Aeronautics and Space Engineering Board, the Panel on Earth Science Applications and Societal Needs, the Science Panel of the Review of NASA Strategic Roadmaps, and the Committee on a Survey of the Scientific Use of the Radio Spectrum.

DARREN S. McKNIGHT is the technical director at Integrity Applications, Inc. (IAI). He is focused on space systems/environment analysis, sustainable energy modeling, innovation practices, visualization solutions, and data analytics. Before coming to IAI, Dr. McKnight served as senior vice president and director of science and technology strategy at Science Applications International Corporation and as chief scientist at Agilex Technologies. His responsibilities included technical collaboration corporate-wide, strategic technology investments (including independent research and development), and validating innovation methodologies. Dr. McKnight has served recently on the Defense Science Board Summer Study on 21st Century Strategic Technology Vectors, National Science Foundation's (NSF's) Industry Expert Panel on Industrial R&D, Harvard Business Review Advisory Council, National Knowledge and Intellectual Property Management Task Force, and IBM's Global Innovation Outlook Team. He has coauthored two technical books, *Artificial Space Debris* and *Chemical Principles Applied to Spacecraft Operations*. Dr. McKnight received his bachelor's degree from the U.S. Air Force Academy in engineering sciences, his master's degree from the University of New Mexico in mechanical engineering, and his doctorate from the University of Colorado in aerospace engineering sciences.

WILLIAM P. SCHONBERG is a professor and chair of the civil, architectural, and environmental engineering department at Missouri University of Science and Technology. He has 25 years of teaching and research experience in shock physics, spacecraft protection, hypervelocity impact, and penetration mechanics. The results of his research have been applied to a wide variety of engineering problems, including the development of orbital debris protection systems for spacecraft in low Earth orbit, kinetic energy weapons, the collapse of buildings under explosive loads, insensitive munitions, and aging aircraft. Dr. Schonberg has published more than 65 papers in referred journals and has presented nearly 65 papers at a broad spectrum of international scientific and professional meetings. He is a recipient of the AIAA Lawrence Sperry Award and of the Charles Sharpe Beecher Prize from the Institution of Mechanical Engineers, is a fellow of the American Society of Mechanical Engineers and the American Society of Civil Engineers, and is an AIAA associate fellow. He received his B.S.C.E. from Princeton University and his M.S. and Ph.D. from Northwestern University. Dr. Schonberg served on the NRC's Committee on Space Shuttle Meteoroid/Debris Risk Management.

STAFF

PAUL JACKSON, *Study Director,* is a program officer for the Aeronautics and Space Engineering Board (ASEB). He joined the NRC in 2006 and was previously a media relations contact for the Office of News and Public Information. He is the study director for a number of ASEB's projects, including proposal reviews for the state of Ohio and the Committee for the Assessment of NASA's Orbital Debris Programs. Mr. Jackson earned a B.A. in philosophy from Michigan State University in 2002 and an M.P.A in policy analysis, economic development, and comparative international affairs from Indiana University in 2006.

JOHN F. WENDT joined the NRC as a part-time, off-site senior program officer for ASEB in 2002. His main activities have involved proposal evaluations for the Air Force Office of Scientific Research and the state of Ohio. He retired in 1999 as director of the von Karman Institute (VKI) for Fluid Dynamics. The VKI is a NATO-affiliated international postgraduate and research establishment located in a suburb of Brussels, Belgium. As director, Dr. Wendt's main responsibility was to ensure the continued excellence of the institute's teaching and research programs by providing effective leadership and administrative and financial management. Dr. Wendt's career at the VKI began as a postdoctoral researcher in 1964. He served as head of the Aeronautics/Aerospace Department and dean of the faculty prior to becoming director in 1990. His research interests were rarefied gas dynamics, transonics, high angle of attack aerodynamics and hypersonic reentry including major inputs to the European Hermes space shuttle program in the 1980s. Dr. Wendt has served as a consultant to the U.S. Air Force, NATO, and the European Space Agency. He is a fellow of the American Institute of Aeronautics and Aerospace. Dr. Wendt received a B.S. degree in chemical engineering from the University of Wisconsin, and M.S. and Ph.D. degrees in mechanical engineering and astronautical sciences from Northwestern University.

LEWIS B. GROSWALD, research associate, joined the Space Studies Board as the Autumn 2008 Lloyd V. Berkner Space Policy Intern. Mr. Groswald is a graduate of George Washington University, where he received a master's degree in international science and technology policy and a bachelor's degree in international affairs, with a double concentration in conflict and security and Europe and Eurasia. Following his work with the National Space Society during his senior year as an undergraduate, Mr. Groswald decided to pursue a career in space policy, with a focus on educating the public on space issues and formulating policy.

CATHERINE A. GRUBER, editor, joined the SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and also worked as an outreach assistant for the National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

ANDREA M. REBHOLZ joined the ASEB as a program associate in January 2009. She began her career at the National Academies in October 2005 as a senior program assistant for the Institute of Medicine's Forum on Drug Discovery, Development, and Translation. Before joining the Academies, she worked in the communications department of a D.C.-based think tank. Ms. Rebholz graduated from George Mason University's New Century College in 2003 with a B.A. in integrative studies–event management and has more than 9 years of experience in event planning.

DALAL NAJIB is the Christine Mirzayan Science and Technology Policy Graduate Fellow with the ASEB. Dr. Najib recently completed her Ph.D. in space physics at the University of Michigan (AOSS department) on modeling the interaction of non-magnetized planets (Mars, Venus) with the solar wind, working with Dr. Andrew F. Nagy.

During her doctoral work, she developed a new three-dimensional multi-fluid magnetohydrodynamic model and applied it to Mars and Venus. In parallel, she also completed a master's of public policy from the Gerald Ford School of Public Policy at the University of Michigan with a focus on science and technology policy. Dr. Najib received her undergraduate degree in aerospace and aeronautical engineering from Supaero (Toulouse, France). She is interested in space policy, general science and innovation policy, and efforts to promote cooperation between international science communities.

MICHAEL H. MOLONEY is the director of the SSB and the Aeronautics and Space Engineering Board at the NRC. Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Before joining the SSB and ASEB in April 2010, he was associate director of the BPA and study director for the Astro2010 decadal survey for astronomy and astrophysics. In addition to his professional experience at the NRC, Dr. Moloney has more than 7 years of experience as a foreign-service officer for the Irish government and served in that capacity at the Embassy of Ireland in Washington, D.C., the Mission of Ireland to the United Nations in New York, and the Department of Foreign Affairs in Dublin, Ireland. A physicist, Dr. Moloney did his graduate Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

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Acronyms

ARTEMIS	Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun
ASEB	Aeronautics and Space Engineering Board
CARA	conjunction assessment risk analysis
DAS	Debris Assessment Software
DLR	German Aerospace Center
DOD	Department of Defense
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
GEO	geosynchronous/geostationary Earth orbit
GPM	Global Precipitation Measurement (mission)
HST	Hubble Space Telescope
HVIT	Hypervelocity Impact Technology
IADC	Inter-Agency Space Debris Coordination Committee
JSpOC	Joint Space Operations Center
LEO	low Earth orbit
MEM	Meteoroid Environment Model
MMOD	meteoroid and orbital debris
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OCT	Office of the Chief Technologist
ODPO	Orbital Debris Program Office
ORDEM	Orbital Debris Environment Model
ORSAT	Object Reentry Survival Analysis Tool
OSTP	Office of Science and Technology Policy
PSFT	Propulsion Systems Foundation Technology
R&D	research and development
TRL	technology readiness level
UN	United Nations