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Volume 3: Space Debris Summary Report

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Naka, R ; Author
Canavan, G H ; Author
Clinton, R A ; Author
Judd, O P ; Author
Pensa, A F ; Author

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14. ABSTRACT

This Study was produced by the Air Force Scientific Advisory Board (SAB). It was requested by the Commander Air Force Space Command and approved by the Secretary and Chief of Staff of the Air Force. It covers three topics, each of sufficient depth to be a study of its own: Space Surveillance, Asteroid and Comet Impact Warning for Earth, and Space Debris. NASA personnel predicted in 1978 that collisional cascading would be an important source of new orbital debris, possibly before the year 2000, and, as a result, would make low Earth orbits at Space Shuttle altitudes unusable. In 1991, NASA published an article that said these predictions were reinforced by events in 1986 and 1990. Out of concern that the United Nations might take actions to regulate further the existing Air Force launch debris mitigation procedures, the SAB was asked to recalculate the debris phenomenon. The SAB Committee has shown that cascading is not an issue in the coming hundred years and recommends that the Air Force continue its established launch and on orbit debris mitigation procedures

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Executive Summary[1]

This Study of *Space Debris* is the third part of a threefold study on *Space Surveillance*, *Asteroids and Comets*, *and Space Debris* that was requested by Commander, Air Force Space Command, and approved by the Secretary of the Air Force and Air Force Chief of Staff.

This Summary Report provides an overview of the Committee's findings on *Space Debris*, in particular the issue of collisional cascading, and a summary of the Committee's recommendations. The entire Committee participated in the review of this subject matter. The detailed calculations in specific areas were performed by a panel of the Committee, as listed in the report, and they take primary responsibility for the content and language of the various sections.

Summary. This Study addressed issues in launch, explosion, collision, fragmentation, and decay. It showed the U.S. Space Command (USSPACECOM) and NASA catalogs to be consistent, apart from completeness and extrapolation to small objects, which do not affect USSPACECOM's DoD responsibilities. This Study advanced the interpretation of ambiguous radar data on small objects, and showed that impacts at 900 to 1,000 km would reduce satellite lifetimes slightly without cascading.

Current, official projections were used to bound the effects of future launch and explosion rates. Launch rates to low Earth orbit have fallen sharply due to reduced Commonwealth of Independent States launches and should continue to fall due to the progressive shift to Geosynchronous Earth Orbit (GEO). The benefits of the current debris policy have been real, but appear to have saturated. The Committee performed independent evaluations of catalog collision rates, which are in good agreement with NASA's. The fragmentation rates were found to be an order of magnitude different, however. It found subtle but important differences in treatments of orbital decay, which had caused NASA to overestimate stability issues.

For similar assumptions, this Study and NASA's models yielded similar results; however, there were differences in assumptions. The key issues were the different assumptions used in NASA's analysis of launch, explosion, fragmentation, and decay rates. For current rates, this Study's models produce little debris growth and no cascading at altitudes below 900 km for conditions for which NASA models predict a tenfold growth—largely due to cascading. The difference can be traced directly to the large number of fragments produced per collision in the NASA model, with which this Committee differs.

NASA analyses indicated that the debris around 950 and 1,450 km is strongly unstable. This Study showed that those conclusions resulted from a simplified model and that in the absence of external sources, the current catalog is stable against collisional cascading at all altitudes. External sources from

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[1] The report was essentially completed in 1996. However, at the direction of the Chairpersons of the Scientific Advisory Board, further interactions by the panel with scientists at the National Aeronautics and Space Administration (NASA) helped identify and clarify the nature of the differences that resulted between the conclusions of this Study and the NASA position on space debris at the time.

The results presented here are based on the Committee's technical analysis completed during the study. While more recent research may have changed some of the comparative results, the recommendations developed remain valid and actions have been taken on several.

launch, deployment, and explosions can cause secular growth that must be reduced before cascading can reach self-sustaining levels. Low altitudes should be addressed within a few centuries; high altitudes could require attention somewhat sooner. With respect to this latter point GEO fragments are spread over very large volumes, which fact greatly reduces collision and growth rates, so the debris problems at GEO should be modest for the foreseeable future.

New knowledge on space debris collisional cascading has been presented here. The reader should note that if any of the input parameters such as launch rate change, the effects must be recalculated.

Recommendations. The study results show that the cascading of space debris will not be an issue in the coming century. It would be appropriate for the Air Force to continue to monitor the rates of launch, explosion, collision, and decay as well as the amount and composition of catalog debris with its current sensors as part of its responsibility as the DoD agent for space. It would be appropriate for the Air Force to establish a nucleus of expertise in space measurements, data analysis, laboratory experiments, and modeling. It would also be appropriate for the Air Force to increase its involvement in interagency and international debris efforts, publish scientific papers on expected space environments, and broaden inputs to its models and empirical parameters for debris prediction.

In summary, the recommendations are that the Air Force should:

- Assume a more active national and international role in space debris
  - Provide substantive representation at interagency and international meetings
  - Establish systematic monitoring of the debris environment
  - Provide primary leadership and point of contact for the DoD
- Develop a better capability to characterize the space debris environment
  - Establish a debris model independent of the NASA model
  - Task Massachusetts Institute of Technology Lincoln Laboratory to analyze Haystack radar data to determine whether further measurements are required
- Provide independent assessment of the debris problem
  - Establish a nucleus of expertise in space measurements and data analysis
- Continue monitoring space launches, explosions, and catalogs
  - Calibrate Air Force sensors to track space debris
  - Complete modification and deployment of charge-coupled device–improved Ground-Based Electro-Optical Deep Space Surveillance
- Continue established launch and on-orbit debris mitigation procedures

Since this Study provides new analyses and results that could affect national space policy, the Committee recommends that a new review by the National Academies be convened to address any unresolved issues.

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Acknowledgments

The United States Air Force Scientific Advisory Board and the Ad Hoc Committee on *Space Surveillance, Asteroids and Comets, and Space Debris* acknowledge the participation of and express thanks and appreciation to Air Force and NASA organizations for their outstanding support throughout this Study. Their genuine interest, encouragement, and cooperation made this Study possible. We are especially thankful for the participation in the Study by representatives of U.S. Air Force Space Command, the Space and Missile Systems Center, Phillips Laboratory, and the National Reconnaissance Office.

Special thanks are likewise due to the staff of the Air Force Space Command, who facilitated all phases of this Study. Thanks also to the staffs of the Air Force Scientific Advisory Board and to ANSER (Analytic Services Inc.), who assisted in the final outbriefings and preparation of the report. Their dedication and untiring support of our Study did not go unnoticed.

F. Robert Naka

For the Committee,
F. Robert Naka, Chairman
1 November 1996

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Space Debris Summary Report[2]

This Study of *Space Debris* is the third part of a threefold study on *Space Surveillance, Asteroids and Comets, and Space Debris* that was requested by the Commander, Air Force Space Command, and approved by the Secretary of the Air Force and Air Force Chief of Staff.

This Summary Report provides an overview of the Committee's findings on *Space Debris* and a summary of the Committee's recommendations.

Introduction

Spent spacecraft, orbit injection rocket stages including boosters, transfer stages, and fragments are potential hazards to active manned and unmanned spacecraft, and several studies have concluded that collisions between them could produce a cascade of particles that could preclude activity in Low Earth Orbit (LEO) in 25 to 50 years. These possibilities had generated pressure for constraints on military space operations, so the Air Force Scientific Advisory Board (AF SAB) was asked to perform an independent study of technical aspects of the debris problem. Most of the technical work on space debris has been performed by the United States Space Command (USSPACECOM), the Air Force Phillips Laboratory, and the National Aeronautics and Space Administration (NASA). All were very cooperative. The NASA work provided the principal technical basis for the conclusions stated in the references cited below.[*]

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[2] The report was essentially completed in 1996. However, at the direction of the Chairpersons of the Scientific Advisory Board, further interactions by the panel with scientists at the National Aeronautics and Space Administration (NASA) helped identify and clarify the nature of the differences that resulted between the conclusions of this Study and the NASA position on space debris at the time.

The results presented here are based on the Committee's technical analysis completed during the study. While more recent research may have changed some of the comparative results, the recommendations developed remain valid and actions have been taken on several.

[*] According to D. Kessler ("Collisional Cascading: The Limits of Population Growth in Low Earth Orbit," *Advances in Space Research*, Vol. 11, No. 12, 1991), pp. 63–66, "In 1978, collisional cascading was predicted to be an important source of new orbital debris, possibly before the year 2000. These predictions were reinforced in 1986 and 1990.… In the long term, once a critical population density of objects is reached, the rate of fragment production from random collisions exceeds the rate of decay.… Once critical density is reached, the debris will increase without placing any more objects into orbit."

The National Research Council in *Orbital Debris* (Washington, DC: National Academy of Sciences, 1995), pp. 2 and 161–163, states, "The resulting debris environment is likely to be too hostile for future space use … Growth in the amount of debris threatens to make some valuable orbital regions increasingly inhospitable to space operations over the next few decades … The model predicts that … objects larger than 1 cm increasing to 250,000 in the next 50 years—not including the effects of collisions. When the effects of collisions are factored in, the future increase to the population is more than 200,000 additional fragments."

According to the Office of Science and Technology Policy report *Interagency Report on Orbital Debris* (Washington, DC: Office of Science and Technology Policy, 1989), pp. 12, 13, and 51, "Mathematical models indicate that a continuing escalation of the normal traffic model with no further debris controls could lead to a critical density

The Committee conducted an independent analysis of some of the principal factors and did comparisons with previous work. The analysis treated radar and optical observations; launch, explosion, and decay rates; and the number and distribution of fragments from explosions and collisions. This made it possible to address hazards to manned spacecraft at low altitudes and the possibility of cascading at higher altitudes.

The Committee reached different conclusions from the cited studies. It determined a much lower likelihood of collisional cascading at both low and high altitudes. The main differences in the assumptions and the technical analysis are identified, and the impacts are quantified.

Analysis

Catalog Comparisons. This Study compared estimates of the amount and size of debris at all altitudes. The USSPACECOM catalog contains objects that range from fragments with diameters of tens of centimeters to large intact objects with areas of hundreds of square meters. The Study used USSPACECOM catalog ephemerides, together with NASA’s averaging techniques, which it tested independently, to compare USSPACECOM and NASA debris fluxes, which agreed very well. As both are ultimately based on USSPACECOM observations and the USSPACECOM catalog, this was primarily a test of data consistency and averaging techniques.

The main unresolved issues were the resolution of ultrahigh frequency (UHF) sensors, which is needed to predict the frequency of Shuttle avoidance maneuvers, and NASA’s extrapolation of catalog measurements to ≈ 1-cm sizes to predict shielding requirements. The former is a matter of the sensitivity and calibration of the UHF radars, which are not maintained for this purpose; the latter is an extrapolation the USSPACECOM resists because particles that small are not observable with UHF radars. Neither issue impacts USSPACECOM's ability to execute DoD missions, although these issues do degrade environment predictions for other applications.

Impact Rates. The Committee reviewed debris density and flux data at Space Station and Shuttle operating altitudes of 400 to 500 km, where the Massachusetts Institute of Technology (MIT) Lincoln Laboratory Haystack X-band radar should give reliable measurements of the flux of particles larger than 1 cm. The then current NASA model and Haystack data as of 1996 gave impact probabilities by particles larger than 1 cm of a few percent per year. Haystack data are sensitive to resonances in radar cross sections, and lack of correlation between space and laboratory debris distributions could further

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sometime before the middle of the 21st century, and an unstable environment could occur sometime in the latter half of the 21st century … Collisional breakup of space objects will become a source for additional orbital debris in the near future, possibly before the year 2000. Over the longer period of time, the orbital debris environment will increase with time, even though a zero net input rate may be maintained. Ultimately, this could lead to a stable but hazardous situation or, worse, an unstable environment with a subsequent cascading effect.… Left unchecked, the growth of debris could substantially threaten the safe and reliable operation of manned and unmanned spacecraft in the next century.”

The Committee papers cited here in footnotes 4, 5, and 6 contain 134 references, citations, and footnotes.

reduce impact rates. Planned modifications could greatly improve optical sensors' performance, but they were not cross calibrated with radars sufficiently well to resolve the issues above.

The then currently agreed-on flux of particles larger than 1 cm that was used to define the hazard to manned flight gave results about an order of magnitude lower than that used in the National Research Council (NRC) book *Orbital Debris*, the Office of Science and Technology Policy (OSTP) *Interagency Report on Orbital Debris*, and the United Nations Committee on Peaceful Uses of Outer Space deliberations. This reduces the hazard and should modify the conclusions and recommendations in these reports.

At the 800- to 1,000-km altitudes of meteorological, remote sensing, and communications satellites, Haystack data roughly agree with the NASA model for particles larger than 1 cm. They would reduce the lifetimes of large satellites a few percent, which is within uncertainties in current amortizations. Collisions of subcatalog particles with satellites would not multiply. Catalog particles are more effective. Using Haystack data for particles larger than 10 cm would produce only about 0.005 particles/year per 40-m^2 satellite, which is small compared to orbital decay. Thus, the direct use of Haystack data indicates that debris is not a threat to current or projected constellations by impact or cascade. However, the large error bars on the Haystack data for debris sizes greater than 2 cm raise uncertainties about the data and their use in such projections.

Launch Rates. Launch rates are a principal source of debris growth. This Study cites factors for a considerable reduction in projected launch rates.

Launch rates to LEO are projected to decline by factors of 2 to 4 over the next few decades for two reasons. The first is the twofold decrease in Commonwealth of Independent States (CIS) launches, the associated twofold reduction in the total launch rate, and the threefold reduction in the launch rate to lower LEO perigees since the end of the Cold War. The total number of LEO objects with perigees below 800 km declined by a factor of 2 as the CIS launch rate fell. This large reduction implies a continued decline of LEO debris over the coming decades. The second reason is the rapid shift of defense, commercial, and civil launches from LEO to Geosynchronous Earth Orbit (GEO) for operational reasons, which should cause the number of GEO launches to reach parity with LEO within the decade and exceed them in subsequent decades. Without the few tens of launches per year planned to support LEO communication constellations, launch rates to LEO would fall an order of magnitude below the levels of the previous decade described in earlier NASA, NRC, OSTP, and UN reports.

This Study estimates that the launch rate to LEO will be approximately 30 per year. This is based on the 1995 launch rate and includes a projection based on the Moorman report. NASA used a 5-year rolling average, which in some early publications was estimated to be as high as 120 per year.

Debris Composition. The major sources of debris are spacecraft, rockets, operational objects, and explosion fragments. The number of spacecraft and rockets on orbit has grown monotonically. About 40 percent of those launched are still in space, where they constitute about 40 percent of the total debris. There have been about 120 explosions, which have historically produced about 7,000 LEO fragments, or an average of ≈ 60 fragments per explosion. Some NASA estimates use 300 fragments per explosion. If 300 fragments per explosion were applied to all 120 explosions, the result would be 36,000 objects, which is 50 percent larger than the total number of objects ever cataloged and 500 percent larger than the number of fragments cataloged in LEO. While fragments are currently the most numerous objects, both they and operational debris stopped growing a decade ago. Thus, rockets and payloads are the only growing parts of the debris. N.B.: The United States Air Force does not claim to be able to detect and catalog particles smaller than 20 cm and particles of these sizes below 800 km would decay. Therefore, we have no way to estimate this effect.

U.S. Space Debris Policy makes minimizing debris a goal for all agencies. The DoD has met this goal by burning boosters to completion to avoid explosions. However, about 75 percent of the fragmentations to date have been of non-U.S. systems, including the CIS explosions that are the greatest threat to long-term stability. Since fragments stopped growing several decades ago, it would appear that most benefits of current U.S. policy were realized before it was put into place. While eliminating fragments altogether would decrease debris only about 30 percent, the alternatives of deorbiting payloads or boosters have 10 to 20 percent penalties, so it is worthwhile to reduce further fragments and operational debris.

Collisions. The Committee independently estimated the debris collision rate, obtaining a total rate of 0.05 collisions per year, in good agreement with NASA estimates. The Committee checked this estimate through comparisons with estimates of the total area and mass on orbit, achieving close agreement between the total areas in the USSPACECOM and NASA catalogs. The comparison of total mass on orbit was also close. NASA's mass catalog, which was built up from an inventory of launches and decays, was not examined during the study due to lack of time.

The Committee also surveyed ballistic coefficients of fragments from laboratory railgun tests, field missile explosions, and on-orbit fragmentations. The first two gave consistent results; the on-orbit data were too noisy due to the rough trajectories available during the study for the inference of ballistic coefficients from trajectory decay data. The overall uncertainty in catalog area appears to be a few tens of percent, which does not significantly affect the Committee's analysis or conclusions. As the calculation of collision rates requires only catalog areas, their uncertainties are of the same order. The uncertainties in the masses could be larger, but are not used in the calculations.

Fragmentation. The Committee independently evaluated the catalog debris fragmentation rate, producing a rate of ≈ 2.7 fragments per year. Together with the collision rate of 0.05 collision per year above, that produces 2.7 fragments/year at 0.05 collisions/year ≈ 55 fragments/collision. The number of fragments/collision varies 30 to 50 percent for parameters consistent with those from railgun and Atlas missile explosion tests. The Study's value of 55 to 90 fragments/collision was in agreement with a number of independent analytic and numerical estimates, but not with the then current NASA value of 480 catalog fragments/collision.[3]

The Committee explored this difference through the series of detailed comparison calculations with NASA Johnson Space Center (JSC). A sample NASA calculation and information contained in an

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[3] D. Kessler, "Collisional Cascading: The Limits of Population Growth in Low Earth Orbit," *Advances in Space Research*, Vol. 11, No. 12, 1991, pp. 63–66.

attachment to this calculation provided the necessary information to compare estimates of fragments directly and achieve ≈ 1- percent agreement with JSC's average masses for all collision types. The agreement on average masses in catastrophic collisions is on the order of 6 percent, which is within the uncertainties in averaging procedures, once it is recognized that only 52 percent of the collisions in JSC's table were catastrophic.

Proper averaging of JSC's debris and collision frequency distributions leads to a prediction of 102 fragments per collision for JSC's highly cascaded distributions. JSC's production rate exceeds that by about 90 percent due to their choice of the exponent used in the fractionation kernel. This Study's results are based on the exponent inferred from the DoD impact experiments which agrees with the predictions of the Fragmentation Algorithm for Strategic and Theater Targets (FASTT) model developed by the Defense Nuclear Agency (DNA) to model those experiments. NASA has cited those experiments but used a different exponent, which produced predictions that were inconsistent with the experiments.

A simple summary of the comparison is that at the time of this Study, for the highly cascaded debris distributions provided by JSC, the factor of ≈ 4 difference between the Study and NASA estimates of fragments per collision resulted from the product of two factors of approximately 2. The first factor resulted from JSC's use of a fragmentation exponent that appeared inconsistent with the DoD test data on which it is nominally based; the second resulted from the characterizations of catastrophic and total collisions in JSC's statement of its fragment production rate. These factors are accounted for in this Study's estimates. The Study was not able to obtain NASA estimates of production rates for current debris distributions to use as a basis for comparison of the Study's value of 60 to 80 fragments per collision.

The earlier NASA estimate of 480 particles per collision overestimated the number of catalog fragments per collision by an order of magnitude relative to theory and laboratory, field, and impact experiments, predicting levels of cascading in a few decades in those NASA calculations that would take centuries in this Study's calculations. NASA's results based on this assumption were the basis for the assessment of debris growth in *Orbital Debris*, the *Interagency Report*, and the UN reports.

Orbital Decay. The Committee examined the consistency of USSPACECOM and NASA catalogs of fragments from past explosions and confirmed that they decay to the present debris distribution, which served as a test of debris production, averaging, and decay algorithms. That also bounded the models that can usefully model debris growth and decay, although it did not explicitly evaluate the models used by USSPACECOM and NASA, which were not fully documented in the literature. The approximate version of orbital decay used in NASA stability calculations can significantly overestimate fragment lifetimes because of its use of a single-component particle distribution, which cannot treat both the small fragments and the large, intact objects correctly. This is particularly true in the altitude bins at 950 km and 1,450 km.

Debris Growth. This Study's analytic and numerical models were tested by using them to predict accurately the current LEO catalog before using them for predictions for comparisons with NASA's. For consistent inputs, the Study and NASA analyses agreed, predicting approximately the same debris growth rates for what are thought to be the same input parameters. For historical launch and explosion rates, 60 fragments per explosion, 80 fragments per collision, and standard orbital decay, the Committee's model predicts little debris growth and no cascading for the next few centuries. The number of objects predicted increases due to the accumulation on orbit of fragments from launches and explosions, to which cascading adds only a few percent. In contrast, the NASA model predicted tenfold growth, 60 percent of which is from cascading. The difference could be traced to the use of 480 fragments per collision, as discussed above. These NASA calculations were the principal projections cited in *Orbital Debris* and the *Interagency Report*.

Stability. NASA had concluded that the debris in the 950-km and 1,450-km peaks is unstable. Those conclusions resulted from the use of a single-component, large-object model, which does not properly treat the stabilizing effect of the rapid decay of smaller fragments. This Committee developed a two-component model that properly includes these fragments and effects. When the components are treated as identical, the model reduces to a one-component treatment and recovered the NASA result that the densities at the two peaks are unstable. When the smaller fragments are treated, their more rapid removal stabilizes the distribution and reduces the rate of production of fragments. In the absence of external sources, the two-component catalog was stable at all altitudes. The stability margin is large below about 1,300 km, and narrower but finite at higher altitudes.

External sources from launch, deployment, and explosions dominate stability above about 900 km, where they cause secular growth that must be stopped before the debris density reaches levels where cascading is self-sustaining. When the two-component analysis was applied to these long-term issues, it appeared that the peak at 950 km could require action in a few hundred years, although the projected order of magnitude decreases in sources there should maintain strong stability until then. The peak at 1,450 km could require action in decades to centuries, depending on whether the CIS resumes launches to that altitude and on the localness of fragment deposition from explosions and collisions there.

These stability issues impact the efficacy of various proposed mitigation measures. NASA's one-component analysis was based on large objects, so it suggested immediate de- or re-orbit of all large objects. Study of two-component results indicates that growth at 950 km can be addressed on a time scale of several centuries, but that sources at 1,450 km should receive earlier, international attention. This Study's analysis indicated a strong stabilizing role of the removal of the small fragments, so it indicates that launch and explosion rate reduction would be as effective as the management and removal of large objects. Both contribute, apparently about equally.

GEO Fragments. GEO fragments are spread over volumes several orders of magnitude larger than those at LEO and, thus, impact and growth rates are reduced accordingly. *Orbital Debris*, on the basis of NASA's analysis, showed that 20 explosions would produce less of a debris hazard than the normal meteoroid background at GEO; thus, the debris problem at GEO will remain small for the foreseeable future. Even though most DoD, civil, and commercial launches are shifting to GEO for operational reasons, GEO should remain a relatively clean environment for centuries and the sources at LEO should decline.

Integrated Assessment. The individual assessments discussed above can be integrated into a single sensitivity matrix that gives the major factors that caused the differences between this Study and NASA's.

The total multiplier expressing the overall difference between this Study's conclusions and NASA's conclusions then could be as large as $\approx 4 \times 5 \times 8 \times 3 \approx 480x$. This very high value produced cascading in the NASA calculations. If any of these multipliers is reduced substantially, cascading is delayed for centuries. However, not all of these factors are tested in every calculation, e.g., the debris growth calculations above used NASA's specified fragment growth rate rather than one dependent on the launch rate, and decay lifetimes are primarily an issue in the long term-stability analyses. A more detailed discussion and analysis was independently written by some members of the Study.[4, 5, 6]

Summary and Recommendations

Summary. The Committee addressed issues in launch, explosion, collision, fragmentation, and decay. It showed the USSPACECOM and NASA catalogs to be consistent, apart from completeness and extrapolation to small objects, which does not impact AFSPC's DoD responsibilities. This Committee advanced the interpretation of ambiguous radar data on small objects, and showed that impacts at 900 to 1,000 km would reduce satellite lifetimes slightly without cascading.

Then current, official projections were used to bound the effects of future launch and explosion rates. Launch rates to LEO have fallen sharply due to reduced CIS launches and should continue to fall due to the progressive shift to GEO. The benefits of the current debris policy have been real, but appear to have saturated. This Committee performed independent evaluations of catalog collision rates, which were in good agreement with NASA's. The fragmentation rates were found to be an order of magnitude different, however. It found subtle but important differences in treatments of orbital decay, which caused NASA to overestimate stability issues significantly.

For similar assumptions, this Study and NASA models yield similar results; however, there were differences in those assumptions. The key issues were the different assumptions used in NASA's analysis of launch, explosion, fragmentation, and decay rates. For current rates, this Study's models predict little debris growth and no cascading at altitudes below 900 km for conditions for which NASA models predicted a tenfold growth—largely due to cascading. The difference could be traced directly to the large number of fragments produced per collision in the then NASA model, on which this Committee disagrees.

NASA analyses indicated that the debris around 950 and 1,450 km is strongly unstable. This Study showed that those conclusions resulted from a simple model and showed that in the absence of external sources, the current catalog is stable against collisional cascading at all altitudes. External sources from

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[4] "Comparisons of Space Debris Estimates," G. Canavan, O. Judd, and R. Naka, Los Alamos LAUR-96-3676 (rev.), October 1997.

[5] "Analysis of Hypersonic Impact Test Data," G. Canavan, Los Alamos LAUR-3114, July 1997.

[6] "Comparison of Calculations of Fragment Production," G. Canavan, Los Alamos LAUR-97-3179, August 1997.

launch, deployment, and explosions can cause secular growth that must be reduced before cascading can reach self-sustaining levels. Low altitudes should be addressed within a few centuries; high altitudes could require attention somewhat sooner. With respect to this latter point GEO fragments are spread over very large volumes, which greatly reduces collision and growth rates, so the debris problem at GEO should be modest for the foreseeable future.

New knowledge on space debris collisional cascading has been presented here. The reader should note that if any of the input parameters such as launch rate change, the effects must be recalculated.

Recommendations. The Study results show that cascading of space debris will not be an issue in the coming century. It would be appropriate for the Air Force to continue to monitor the rates of launch, explosion, collision, and decay, as well as the amount and composition of catalog debris, with its current sensors as part of its responsibility as the DoD agent for space. It would be appropriate for the Air Force to establish a nucleus of expertise in space measurements, data analysis, laboratory experiments, and modeling. It would also be appropriate for the Air Force to increase its expertise and involvement in interagency and international debris efforts, publish scientific papers on expected space environments, and broaden inputs to its models and empirical parameters for debris prediction.

In summary, the recommendations are that the Air Force should

- Assume a more active national and international role in space debris
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  - Provide the primary leadership and point of contact for the DoD
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  - Complete modification and deployment of charge-coupled device–improved Ground-Based Electro-Optical Deep Space Surveillance (GEODSS)
- Continue established launch and on-orbit debris mitigation procedures

Since this Study provides new analyses and results that could affect national space policy, the Committee recommends that a new review by the National Academies be convened to address any unresolved issues.

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Appendix A—Task Statement

Space Surveillance, Asteroid and Comet Impact Warning for Earth, and Space Debris

March 1995

Space Surveillance

Background. The Space Surveillance mission has been handled by the Air Force since 1957 when the first Sputniks were launched. The initial facility was at Hanscom AFB and was later moved to the Cheyenne Mountain Complex in Colorado Springs. The mission requirements were largely driven by the Soviet threat for all these years. In fact, the missile warning mission has dominated the space surveillance mission to such an extent that the evolution of capability in the latter has been painfully slow and has lagged the state of the art substantially.

The space surveillance mission area remains an essential part of the Air Force function to support the warfighter with space assets. The threat to space assets and their supporting capability is evolving with the need to monitor an increasingly crowded environment. Operational spacecraft have in general been large objects easily tracked by the space surveillance network.

The most serious problem with the current system is that the theory, software, and hardware used for orbit determination at Space Control Center (SCC) have evolved only slowly over the past 20 years, while the state of knowledge of orbit determination, the state of software and hardware technology, the sensitivity of sensors, and the accuracy of the data have advanced immensely. This has precluded the system from taking advantage of the accuracy of the data to reduce the overall tasking load of the sensors, which at the same time would enable them to contribute more in other areas of space surveillance, such as debris monitoring, and consequently address more areas for the same total cost.

The sensitivity of several sensors has increased significantly in the past 20 years. This has substantially enhanced the number of objects detected. However, processing limitations at SCC have precluded the maintainable catalog from absorbing all these new objects into the database.

In future applications of surveillance data, improved accuracy and the ability to define that accuracy in meaningful terms to the warfighter will be a primary objective. The accuracy of sensors has increased substantially over the past two decades, but the capability to calibrate these instruments on-line to their inherent noise level is only now becoming available with laser instrumentation. The remaining impediment to achieving higher accuracy is the drag environment for satellites operating below 1,000 km, and this will be resolved only when on-line procedures for calibration of the density models are implemented. Finally, as increasing demands on accuracy are made by the user community, alternative filter technologies that can produce covariance products incorporating both the sensor and environmental error models should be considered.

Task Description. The Committee should

- Assess the capability of the current Space Surveillance Network (SSN) with respect to search for new or lost earth satellites or objects, accuracy of measurements, timeliness, and transmission of sensor data to a central catalog station for all altitudes from 150 km to 35,000 km. Include considerations of reducing errors.
- Determine what and how improvements to the SSN should be accomplished.
- Assess the capability of the current earth satellite catalog production with respect to accuracy, timeliness, and dissemination of data products. Include analyses of environmental factors that introduce errors into catalog products and of technologies that define the propagation of these errors into catalog products with high confidence.
- Determine what and how improvements in producing the catalog(s) can be accomplished. Consider the exploitation of computer performance as an opportunity to transition the catalog to a format based upon special perturbations technology with trusted covariance properties embedded into it.
- Assess the benefits of improved accuracy and of the ability to define that accuracy in meaningful terms to Air Force, interagency, and international operations as orbits with desirable properties (e.g., sun synchronous) are exploited by an increasing number of spacefaring nations.
- Recommend appropriate Air Force actions.

Asteroid and Comet Impact Warning for Earth

Background. The growing concerns about the asteroid and comet threat to earth may result in a new mission for the space surveillance system. The capability to integrate and perform this potential mission needs to be assessed as part of the future architecture of space surveillance.

Asteroids and comets have struck the earth over its history in Russia, Yucatan, and the United States (Arizona). It is now believed that an asteroid impact caused the cataclysmic extinction of the dinosaurs. Although impacts are rare, they could have devastating effects. At a minimum the Air Force should consider Deep Space Surveillance as a new mission area.

Task Description. The Committee should

- Review and assess the Asteroid and Comet environment and earth impact rate
- Assess detection and tracking requirements and Air Force capabilities
- Determine and describe appropriate capabilities and missions for the Air Force
- Recommend Air Force actions for these new missions

Space Debris

Background. There is a proliferation of smaller-size satellites on one hand and a large, uncontrolled growth of debris, consisting of dead satellites and fragments from breakups of a variety of sizes, on the other. As a result, there is a significant overlap of the two. Further, there is a growing national concern, driven by the National Aeronautics and Space Administration's (NASA's) requirements for keeping track of debris down to 1 cm characteristic size for safety of manned spacecraft. Hence, the space surveillance system must maintain an orderly and accurate catalog of all objects in space to ensure that the mission is accomplished despite its evolving nature.

The only organized collection and analysis of small Space Debris has been by NASA/JSC, employing modeling and estimates because of the sparse data that have so far been collected. Further, the numbers of objects in the Air Force catalog and NASA's debris curves do not agree where they overlap in the 10- to 100-cm object size range. The Air Force should consider a more active role.

Task Description. The Committee should

- Independently assess the seriousness of space debris as it may affect Air Force assets and space operations.
- Evaluate the dynamics and factors that produce and/or reduce space debris.
- Independently review the models and assumptions for the evolution of the historical space debris calculations and predictions, particularly for the condition of unstable growth known as collisional cascading.
- Review and compare Air Force studies measurements, assumptions models and assessments of space debris with those produced by other government agencies. Determine the reasons for any differences.
- Recommend appropriate Air Force actions.

Potential Impact of the Study

The major result of the Study would be to identify means to enhance overall mission capabilities of the Air Force in the three subjects addressed substantially while reducing operational costs of the system.

The reduction of the manpower and the reduced number of sensor sites required for Space Surveillance, the reduction of the maintenance of the software by using more commercial packages, and minimizing the use of one-of-a-kind software/hardware packages in application will be clarified.

The actions required by the Air Force in the new mission area of Planetary Defense will be identified.

The seriousness of Space Debris and its effects on Air Force space operations will be clarified and any additional efforts required will be identified.

Committee Organization

Chairman	Dr. F. Robert Naka
General Officer Participant	Brig Gen Thomas J. Scanlan, Jr., SAF/ST
Senior Civilian Participant	Mr. John H. Darrah, HQ AFSPC/CN
Executive Officer	Lt Col Donald Jewell, HQ AFSPC

Appendix B—Members and Affiliations*

Dr. F. Robert Naka, Chair
President and CEO
CERA, Inc.
Vice President, Engineering (Ret)
GTE Government Systems Corporation

Dr. Gregory H. Canavan
Senior Scientific Advisor
Los Alamos National Laboratory

Dr. Rankin A. Clinton
Director (Ret)
Army Intelligence Agency

Mr. Theodore Jarvis
Director of Strategic Studies (Ret)
The MITRE Corporation

Dr. O'Dean P. Judd
Laboratory Fellow
Los Alamos National Laboratory

Dr. Antonio F. Pensa
Associate Division Head
AeroSpace Division
MIT Lincoln Laboratory

Maj Gen Robert A. Rosenberg, USAF (Ret)
Executive Vice President and
General Manager
Washington Operations
Science Applications International Corporation

Dr. Edward Teller
Director Emeritus
Lawrence Livermore National Laboratory

Mr. Samuel M. Tennant
President Emeritus
The Aerospace Corporation

Dr. Louis G. Walters
Astrodynamics Consultant

Col Simon P. Worden, USAF
Commander
50th SAF Space Wing

Mr. John H. Darrah
Chief Scientist
HQ Air Force Space Command

Brig Gen Thomas J. Scanlan, Jr., USAF
Director, Space Systems
SAF/ST

Lt Col Donald L. Jewell, USAF
Executive Officer
HQ Air Force Space Command

* *Affiliations as of 1 March 1995*

Panel Organization

Surveillance Panel
Dr. Bob Naka, Chair
Dr. Greg Canavan
Mr. Ted Jarvis
Dr. Dean Judd
Dr. Tony Pensa
Mr. Sam Tennant
Dr. Lou Walters

Space Debris Panel
Dr. Bob Naka, Chair
Dr. Greg Canavan
Dr. Dean Judd

Asteroids and Comets Panel
Dr. Greg Canavan, Chair
Mr. John Darrah
Dr. Dean Judd
Dr. Bob Naka
Dr. Edward Teller

At-Large Members
Dr. Randy Clinton
Maj Gen Rosie Rosenberg, USAF (Ret)
Col Pete Worden, USAF

Appendix C—Committee Meetings

Full Committee Meetings

MIT Lincoln Laboratory, Lexington, MA	8-10 May 1995
MITRE Corporation, McLean, VA	30 May to 2 June 1995
HQ AFSPC, Colorado Springs, CO	19-21 June 1995
Loral Aeronutronic, Santa Margarita, CA	17-19 July 1995
MITRE Corporation, Colorado Springs, CO	18-20 September 1995
Phillips Laboratory, Albuquerque, NM	9-11 January 1996
MIT Lincoln Laboratory, Lexington, MA	20-23 February 1996

Surveillance Panel Meetings

MITRE Corporation, Colorado Springs, CO	28-29 November 1995
Space and Missile Systems Center, Los Angeles, CA	14 March 1996
Cape Cod AFS, MA	19 March 1996

Asteroids and Comets Panel Meetings

Lawrence Livermore National Laboratory, Livermore, CA	22-26 May 1995
Many installations, Maui, Hawaii, and Oahu, HI*	8-12 April 1996

Debris Panel Meetings

Phillips & Sandia Laboratories, Albuquerque, NM	11 August 1995
NASA Johnson Space Center, Houston, TX	16-17 August 1995
NASA Johnson Space Center, Houston, TX	17 October 1995

** Joint meeting with Surveillance Panel*

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Appendix D—Acronyms and Abbreviations

AFSCN	Air Force Satellite Control Network
AFSPC	Air Force Space Command
AMOS	Air Force Maui Optical Station
AMTA	Advanced Multicolor Tracker for AMOS
ASAT	Antisatellite
AU	Astronomical Unit
B	Billion
BMDO	Ballistic Missile Defense Organization
BW	Bandwidth
CCD	Charge-Coupled Device
CINC	Commander-in-Chief
CIS	Compensated Imaging System
CIS	Commonwealth of Independent States
CMC	Cheyenne Mountain Complex
COE	Center of Excellence
COMINT	Communications Intelligence
COTS	Commercial Off-the-Shelf
dB	Decibel
dBsm	Decibels Above One Square Meter
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DOSE	Dynamics of Solid Earth
ELINT	Electronic Intelligence
EO	Electro-Optical
FASTT	Fragmentation Algorithm for Strategic and Theater Targets
FDS	Flight Demonstration System
FISINT	Foreign Instrumentation Signals Intelligence
FOBS	Fractional Orbit Bombardment System
GEO	Geosynchronous Earth Orbit
GEODSS	Ground-Based Electro-Optical Deep Space Surveillance
GPS	Global Positioning System
HAX	Haystack (radar)
HEO	Highly Elliptical Orbit
HIO	Highly Inclined Orbit
IR	Infrared
J	Joule
JSC	Johnson Space Center
kg	Kilogram
km	Kilometer
LANL	Los Alamos National Laboratory
LDEF	Long Duration Exposure Facility

LEO	Low Earth Orbit
LONEOS	Lowell NEO System
LPC	Long-Period Comet
LWIR	Longwave Infrared
m	Meter
M	Million
MIT	Massachusetts Institute of Technology
MLWIR	Medium Longwave Infrared
MOTIF	Maui Optical Tracking and Identification Facility
MPA	Mission and Payload Assessment
MSSS	Maui Space Surveillance Site
MT	Megaton
MWIR	Mediumwave Infrared
NASA	National Aeronautics and Space Administration
NB	Narrowband
NCMC	NORAD Cheyenne Mountain Complex
NEO	Near-Earth Object
NOAA	National Oceanic and Atmospheric Administration
NP	National Program
NSA	National Security Agency
O&M	Operations and Maintenance
RSO	Resident Space Object
RTODS	Real Time Orbit Determination System
s	Second
SBIRS	Space-Based Infrared System
SBV	Space-Based Visible
SCC	Space Control Center
SIGINT	Signals Intelligence
SLBM	Sea-Launched Ballistic Missile
SMTS	Space Missile and Tracking System
SPADOC	Space Defense Operations Center
SSN	Satellite Surveillance Network
SWIR	Shortwave Infrared
T	Trillion
TOA	Total Obligational Authority
TOS	Transportable Optical System
UHF	Ultrahigh Frequency
USSPACECOM	United States Space Command
WB	Wideband

Appendix E—Initial Distribution

Headquarters Air Force

SAF/OS	Secretary of the Air Force
AF/CC	Air Force Chief of Staff
AF/CV	Vice Chief of Staff
AF/CVA	Assistant Vice Chief of Staff
SAF/AQ	Assistant Secretary for Acquisition
SAF/AQ	Military Director, USAF Scientific Advisory Board
SAF/SX	Deputy Assistant Secretary for Space Plans and Policy (2 copies)
AF/IL	Deputy Chief of Staff, Installations and Logistics
AF/ST	Air Force Chief Scientist
AF/XO	Deputy Chief of Staff, Air and Space Operations
AF/XP	Deputy Chief of Staff, Plans and Programs
AF/HO	Air Force Historian

Air Force Space Command

AFSPC/CC	Commander
AFSPC/ST	Chief Scientist (4 copies)

Air Force Materiel Command

AFMC/CC	Commander
AFMC/EN	Directorate of Engineering and Technical Management
AFRL/CC	Commander, Air Force Research Laboratory
AFRL	Space Vehicles (Geophysics) Directorate

Other

AF SAB Co-Chairs
Study Committee
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13. ABSTRACT (Maximum 200 Words)

This Study was produced by the Air Force Scientific Advisory Board (SAB). It was requested by the Commander Air Force Space Command and approved by the Secretary and Chief of Staff of the Air Force. It covers three topics, each of sufficient depth to be a study of its own: Space Surveillance, Asteroid and Comet Impact Warning for Earth, and Space Debris.

NASA personnel predicted in 1978 that collisional cascading would be an important source of new orbital debris, possibly before the year 2000, and, as a result, would make low Earth orbits at Space Shuttle altitudes unusable. In 1991, NASA published an article that said these predictions were reinforced by events in 1986 and 1990. Out of concern that the United Nations might take actions to regulate further the existing Air Force launch debris mitigation procedures, the SAB was asked to recalculate the debris phenomenon. The SAB Committee has shown that cascading is not an issue in the coming hundred years and recommends that the Air Force continue its established launch and on orbit debris mitigation procedures.

14. SUBJECT TERMS Space debris, fragmentation, decay rates, collisional cascading, Space Shuttle, radar data, Air Force Space Command and NASA catalogs, low Earth orbits.

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