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Survey of Space Debris Reduction Methods

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There is no organized program to remove existing debris from orbit. Recent events such as the Chinese ASAT test of 2007 and the collision of Iridium 33 and Cosmos 2251 of 2009 have increased the risk of debris collisions with operational satellites and raised the level of urgency for more aggressive management of orbiting junk. The consensus of opinion is that a requirement for debris population reduction is inevitable if space is to remain freely available for commercial, scientific and security applications. Current debris mitigation efforts are limited to minimizing new debris production. Clearly, space-faring nations must intensify mediation activities and move toward a comprehensive remediation programs in which debris removal is an active part. Many solutions have been suggested, but few will prove viable in terms of technology limitations and cost issues. Additional concerns will contribute to future decisions, such as political and legal issues. However, technical viability and relative cost are of major focus here. The Applied Physics Laboratory (APL) of Johns Hopkins University has been investigating debris removal methods and has conducted a comprehensive survey of potential technological approaches and operational concepts for dealing with the reduction of existing and future discarded orbiting objects. This work represents a first step in the evolution of a practical solution to one of the most challenging and complex issues facing the future of space flight. The work presented here is intended to be an early step toward framing the problem space, identifying realistic options and identifying preliminary metrics for later decision processes.

I. Introduction

SEVERAL organizations among the world's space-faring nations are concerned about the increasing risk of space debris interfering with operational satellites. Although no one knows when this will turn into a crisis, there is general consensus that sometime in the next one or two decades the frequency of collision events in congested orbital regions will dramatically increase. The result will be a loss of access to an important part of space. However, the world cannot stop using space applications. The benefits are simply too important and they have become an integral part of modern living. The options seem obvious: proactively anticipate a logical progression of adverse events and continue existing mitigation programs with an expansion into remediation programs; or, simply ignore the inevitable and do nothing until access to space is threatened or denied. In other words, choose to expend a low level of resources over a long period of time, or wait and expend a great deal of resources later, after critical space assets are no longer operational.

While the space debris concern is a recent phenomenon, the accumulation of discarded objects started at the dawn of the Space Age on that fateful October day in 1957, when the USSR launched Sputnik 1. No one had an inkling that the exploration and exploitation of space would eventually lead to the trashing of Earth orbits. Nevertheless, as the number of launches increased through the 1960s, expired satellites began to accumulate in a variety of orbits. The rate of satellite launches exceeded 100 per year within 10 years[1] and reached an all-time high of 129 in 1984. Every space launch creates some trash in the form of large and small debris objects. Often, the large items consist of partial or whole upper stages and satellites that have ceased to operate. Over the years in orbit, many expended upper stages and satellites break up, explode or are broken up by collisions with other objects.

As early as 1970, NASA began funding research activities at the Pennsylvania State University[2] to investigate ways to retrieve expired satellites from orbit. This work addressed the capture of large uncontrolled objects that might be spinning or tumbling. Some of the resulting ideas may be used if a debris reduction program is implemented. Later, when NASA began internal debris studies there were less than 2000 objects cataloged by the Department of Defense. At that time collision risks were not considered significant except for very large space structures.[3] As the debris population expanded, studies became focused on the sources of small debris objects. By 1980, NASA concluded that explosions of Delta second stages and USSR satellite tests were major contributors to

*Senior Professional Staff, Space Systems Applications Group, Space Department. AIAA Fellow space debris. In 1981, the American Institute of Aeronautics and Astronautics (AIAA) issued a position paper on space debris in which the risk issues of space debris were identified. That paper called for real action to mitigate future catastrophic collision events.

It has been 28 years since the initial alarm was sounded by AIAA. In the interim several mitigating actions have been implemented by space-faring nations. For example, Delta upper stages are now prevented from exploding by simply venting residual propellant. Many satellites now use added debris shielding to ensure survival in the event of one or more small object collisions. A strategy of evasive maneuvers has been established for some classes of satellites. As a major mitigation step most new satellites incorporate the ability to either de-orbit or maneuver away from active spacecraft as they reach mission expiration. In order to assist in predicting potential collision events mitigation there are extensive government and private sector tracking and simulation activities related to anticipating collisions probabilities among spacecraft and debris objects. However, one important factor in affecting the ability to track a debris object is its size. Current ground-based tracking facilities can generally observe objects that are at least 10 cm in size. As of mid-2009, the number of these objects is estimated to be well over 10,000, including active spacecraft. In spite of ongoing mitigation programs the debris problem continues to grow, in large part because many nations continue to launch new satellites and conduct in-orbit tests.

II. Debris Characteristics and Mitigation Activities

Space debris is also known as *space junk*, *space waste* or *space trash*, but whatever the name, it consists of a large number of objects in sizes that span at least seven orders of magnitude from a few microns to several meters. All of these objects are circling Earth in orbits that range in altitude from about 300 km to well over 35,000 km. All of these objects are traveling in independent orbits with speeds ranging from over 7 km/sec down to 3 km/sec, respectively. These objects are both the product and waste of the Space Age that began in 1957 and continues today with an annual orbit insertion rate in excess of 100 spacecraft. Over the last 10 years the world has averaged an annual rate of 66 space launches, many of which carry multiple satellites. A handful of spacecraft have left Earth for heliocentric endeavors, but the vast majority of these are satellites that remain under the influence of our home planet.

A number of international agreements have been negotiated in the last few years for the purpose of limiting the rate of debris growth.[4] Nevertheless, recent events have exacerbated the risk of debris collisions with operational satellites. A single anti-satellite weapons test by China in early 2007 resulted in an instant increase of low orbiting debris by as much as 25 percent. On February 10, 2009, just before noon in Washington, DC, the first catastrophic collision between to complete satellites took place over Siberia. The operational telephony satellite, Iridium 33, collided with an expired Russian communications satellite, Cosmos 2251, resulting in two debris clouds and increasing the space debris count of trackable pieces by at least several hundred. The closing speed was estimated at over 6.7 km/sec at an altitude of 790 km. These two events have had the effect of increasing the level of debris collision risk from one of a minor awareness to one of growing concern. All space-faring nations are sensitive to the debris issue and acknowledge this as a serious threat to future access and use of space. Left unattended, orbital collisions will increase until many satellites become disabled or destroyed. It is simply a matter of time before the frequency of impacts in congested orbital regions increases along an exponential path, an effect similar to a *chain reaction*.[3]

Prior to 2007, debris population numbers and spatial distributions were such that simple mitigation approaches were considered satisfactory. Today, the effectiveness of these approaches is in serious doubt. The loss of Iridium 33 eliminated any remaining doubts concerning the seriousness of the debris threat. It is certainly time to move from simple debris mitigation activities toward comprehensive debris remediation programs that involve all current mitigation steps plus a permanent activity to address active reduction of collision risks. To achieve lower, acceptable risk levels, two areas of debris control appear to be necessary. First, a reduction in certain debris-debris collisions must be implemented. Second, large debris objects must be removed from zones of high congestion. These seem to be daunting challenges, but they must be addressed.

Multiple surveys have yielded both possible and improbable debris removal techniques. However, most of the suggested solutions are generally perceived as physically impractical, prohibitively expensive and/or having negative environmental side effects. Nevertheless, there are several good ideas within the suggested concepts. Over the past year the Applied Physics Laboratory (APL) has conducted an ongoing effort to identify debris removal concepts from many sources, extract promising ideas from many suggestions and reformulate these ideas into potentially realistic approaches. Many concepts have appeared in the literature over the decades, but few have been evaluated in view of current and future constraints, technological advances and relative costs. Furthermore, a single approach to debris removal is not going to be sufficient to satisfy all requirements. There are, however, two separate but areas of concentration: small debris removal and large debris capture. The specific methods presented here focused on one or both of these areas.

III. The Nature of the Challenge

At any moment there are several hundred operational satellites flying above Earth, with all other orbiting objects classified as debris. Such objects include expired satellites, spent rocket upper stages, fragments from explosions and collisions, paint flakes, chunks of slag from solid rocket motors, remnants of old science experiments and a variety of small particles. If left alone debris will continue to propagate through collisions, launches, mishaps, explosions and the expiration of active satellites. With each passing day the risk of damage to active satellites increases. Eventually, a phenomenon called the *Kessler Syndrome*[5] may lead to the destruction of many operational satellites in low orbits. In fact, movement toward this phenomenon has already begun to take shape. On the average, debris numbers are increasing and average sizes are decreasing. At some point in the not-too-distant future, and in highly populated spherical shells about the Earth, there could be a chain reaction of collisions as the frequency of events accelerates exponentially. Once this process begins most active satellites in these congested orbits will rapidly be reduced to a large number of small debris pieces. The resulting cloud of particles could act as a barrier to space flight, preventing penetration by satellites and launch vehicles. Should this situation occur, space access could be denied to all space-faring nations until this debris shield is at least partially cleaned up.

The time to act is well before the frequency of debris collisions starts to increase significantly. A responsible, measured removal program that reduces and maintains risks to active satellites at acceptable levels is the prudent solution to long-term access to space. Otherwise, every industrial nation could experience major economic downturns and severe security breaches. All modern banking, communications, navigation, weather forecasting, intelligence and defense systems would be affected.

From a marco-scale view of the debris threat, the main regions of concern are bounded by the orbital altitudes which are popular for operating satellites. Figure 1 illustrates the evolution of the total trackable low orbit object population since 1994. Note the dramatic impact of two events: the Chinese ASAT test of 2007 and the Iridium/Cosmos collision of February 10, 2009. Unfortunately, object peaks shown in this figure correspond to regions of desired orbits for operational satellites. Figure 2 is a histogram of all LEO objects tracked by the Department of Defense as of July 1, 2009.

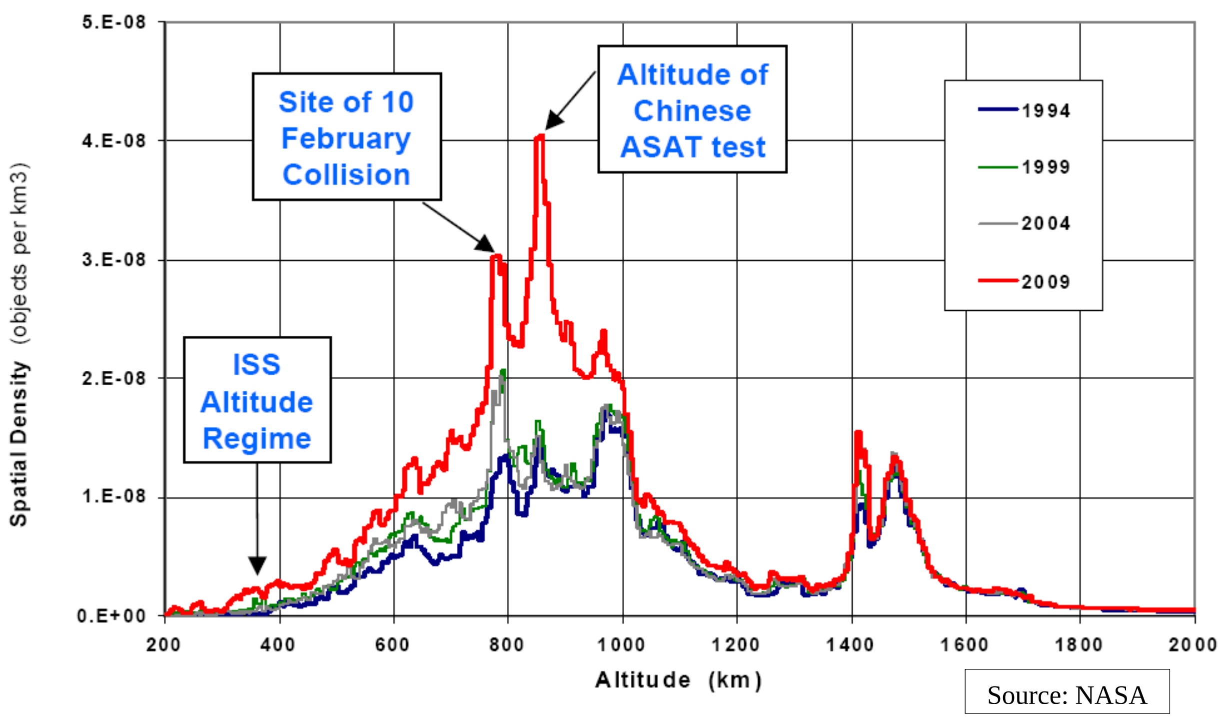

Figure 1. Graphic evolution of total trackable low Earth orbit (LEO) object population since 1994.

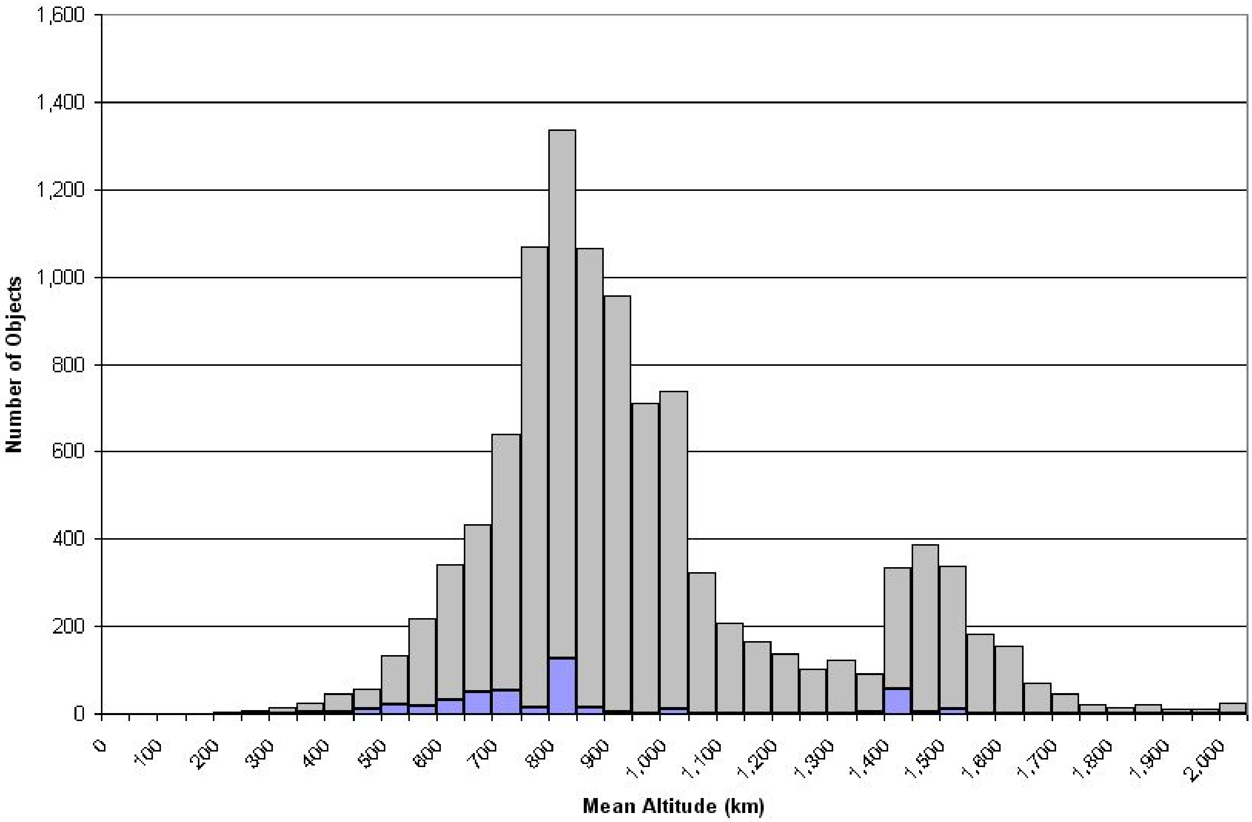

Figure 2. Histogram of all tracked LEO objects as of July 1, 2009. Active satellites are depicted in blue.

The combination of high debris counts and active satellite populations indicates that one altitude range of interest for object removal might be 800 km to 1100 km. If the spherical shell bounded by this range were to be cleared of debris, the threat to active satellites would be greatly reduced. From specific mission and operational points of view other parameters, such as inclination, eccentricity and longitude of the ascending node will come into play. However, if a major debris reduction program were to be established, altitude would be of prime importance.

The space environment is difficult to comprehend. Once a satellite reaches orbital speed it is travelling in a hard vacuum around the Earth. If it is at an altitude below about 500 km, any residual atmospheric molecules will tend to drag a satellite back toward Earth, even though it may take years or decades to decay such orbits. For higher orbits there is no measurable decay and orbits tend to last very long times. Even though satellites travel at about the same speed at similar altitudes, they are not generally travelling in the same directions, because they travel in different planes. Two satellites in circular orbits at the same altitude have the same speed, but in a collision, their relative speed could be anything from near zero up to 15 km/sec for low orbits. In geostationary Earth orbits (GEO) closing speeds are much lower for two reasons: the GEO orbital speed is just over 3 km/sec; and satellites travel in planes that are close to each other and in the same direction. Thus, closing speeds at GEO tend to be less than one km/sec.

Imagine several hundreds of thousands of debris pieces in low Earth orbits, all travelling in individual planes about the planet. Roughly 15,000 of these are larger than 10 cm and an estimated 100,000 debris objects are between one cm and 10 cm. Overlay another several million sub-centimeter pieces on this environment. Now, try to imagine how to remove enough of the debris to make space flight safe for future generations.

IV. Spectrum of Debris Removal Approaches

The space debris reduction challenge seems sufficiently complex that a full spectrum of solutions must be considered, from *do nothing* to the creation of a whole new space program that does nothing but reduce the debris population. Experience with complex challenges has taught that an understanding of extreme options is required before practical approaches can be identified. First, the two extremes are discussed, followed by a practical option. Finally, a few exotic ideas are presented.

A. The *Do Nothing* Approach

The *do nothing* approach represents one extreme option. However, it does not literally mean "do nothing," because a debris mitigation program is already in place. In fact, over the last few years, the rate of increase of debris population from newly launched satellites has been reduced. Active maneuvering is being used in a small number of cases to mitigate high-probability-of-collision threats. Many satellites carry added shielding to survive encounters with very small debris objects. Here, the expression *do nothing* implies limiting debris remediation activities to those already under way. There would be no effort to remove any of the already established debris nor any new debris resulting from explosions, breakups and collisions.

Existing and new debris would be left to its own natural propagation and proliferation for the foreseeable future. From the point of view of operational spacecraft, the risk of encountering debris objects would continue to increase, especially at highly congested orbital altitudes. Survival would become increasingly difficult. In those instances where satellites became disabled, other spacecraft would have to replace them. To exacerbate the situation even further, disabled satellites might no longer have the ability to maneuver away from orbits of replacement satellites, further increasing risks to replacement and other nearby satellites. Ultimately, continued use of highly congested regions plus replacement of old and addition of new satellites would assure an eventual chain reaction of collisions in which at least a significant portion of space assets would be disabled and/or destroyed. The resulting debris field would preclude further replacement of space assets in high-debris regions, resulting in denial of access to much of near-Earth space and creating much higher risks to launching spacecraft through debris fields. Eventually, large portions of the space volume would reach a Kessler Syndrome state. In other words, there would be spherically symmetrical altitude zones around Earth in which debris would be more or less homogeneously distributed with sufficient density to significantly shorten expected life times for new operational satellites.

Since a new complex space debris removal program would require development times of at least several years, and possibly up to 10 years or more, it is likely that the *do nothing* option will continue toward the Kessler Syndrome scenario for some time regardless of any decision process. Furthermore, it is likely that no serious investment in debris removal programs will be made until debris-satellite collision risks reach an "unacceptable" level, i.e., when the cost/benefit ratio reaches a point where the benefits outweigh the costs of a debris removal program. Note that this scenario may have some positive effects on the cost of debris removal. For example, if the situation is allowed to decay to the point of converting congested satellite regions to debris-only shells about the Earth, then a debris removal program can focus on the debris without concern for operational spacecraft in the region. As a result, the logical clean-up philosophy would encourage an all-out attack on debris using uncontrolled collection for small objects and de-orbit methods for large objects. The advantages would include lower costs, simpler devices and relatively short clean-up schedules. Of course, the down-side of delaying until operational satellites are destroyed by debris is the inability to use debris-ridden regions for some time, during which the clean-up program is developed and carried out. This interval would most likely be measured in terms of years.

B. The *Do Everything* Approach

The *do everything* approach represents the other extreme option. This approach requires the addition of active debris removal measures to existing mitigation programs. Current mitigation actions effectively limit the rate of future debris build up, thus helping to slow collision risk increases for operational satellites. It is the current and unavoidable new debris that would be addressed in this approach. Timing is important. We know that the biggest producer of debris is result of collisions between small debris and large expired and partial satellites and upper stages. Thus, the most important function of the *do everything* approach is the elimination of expired satellites, upper stages and large pieces of either. Elimination of large objects will likely require the use of large spacecraft that can rendezvous and capture each item, one at a time. Such spacecraft could be robotic or crewed, but safety and economic issues will likely dictate the use of robotic vehicles.

Small debris elimination, it seems, can best be addressed through the use of uncontrolled robotic vehicles that allow objects to randomly impact collection devices, i.e., mechanisms that can withstand small-debris impacts without creating additional debris. A number of such devices that are discussed later. Over a period of time the number of small debris pieces will diminish and allow collision risks to decrease. The primary objective of the *do everything* approach is to rapidly eliminate enough debris from congested zones to effectively rein in collision risk factors.

C. A Seemingly *Practical* Approach

It is too early to determine which future approach will be best, or even practical. However, based on what is now known, there are a few observations that address potential practical solutions. The two extremes outlined above were selected because they represent limiting options. After some thought it should be clear that the best approach to debris reduction will surely fall between *do nothing* and *do everything* extremes. Nevertheless, that solution will contain elements of both extremes, and it will most likely involve the continued use of space for exploration and exploitation during clean-up activities.

Whatever approach is selected it must satisfy several requirements. It must be cost-effective, because debris clean up is not perceived as adding value to space applications or exploration. However, debris removal will enhance the use of space by rendering orbital usage relatively safe from collisions. The solution must not result in additional debris that may be generated from clean-up operations. Removal operations must be reliable in order to assure satellite operators that space access will continue without interruption. Such operations must be timely in that they must reduce debris fast enough to counter new debris creation while reducing risks to operational satellites. Debris reduction activities must be transparent to normal space activities. In addition, any approach must be politically and legally acceptable to all space-faring nations. Thus, before any of these characteristics are implemented, a majority of space-faring nations must agree that such a program is necessary and worth the necessary investments. As a potential alternative, a commercial/private-sector venture might be able to create a new business opportunity that could attract sufficient financing to fund a business plan. Of course, this latter approach will still require political and legal agreement among nations.

D. A Few Exotic Approaches

There are several debris reduction concepts that seem to be well beyond current technology or appear to be *far-fetched* at first glance. However, some of these may one day be realized, or at least, spark the imaginations of some innovative minds to produce better solutions. Two of these *out there* concepts are included as "food for thought."

The first approach takes advantage of the *do nothing* philosophy in which current highly-congested orbital regions are allowed to experience exponential increases in debris-collision events. Assume that all operational satellites in these zones are transformed into useless debris. One subsequent option was already mentioned, a massive and expensive debris clean-up program in which the denied zones are freed of enough debris to reduce risks and permit continued use of these regions for future satellites. During the several-year period in which operational satellites are reduced to debris, alternate, non-optimum spacecraft that can be placed in less-congested orbits in order to act as temporary replacement platforms providing services not otherwise available. Eventually, previously denied orbits will again be available for satellite re-population.

The other *far-fetched* approach makes use of the Earth's atmosphere to remove debris. It is well-known that solar flare activity affects the atmosphere. During high flare activity, the atmosphere it bulges and creates a high-drag environment for all orbiting objects passing through these bulges. Once again, consider the *do nothing* scenario in which only debris remains in near-Earth orbits. A clean-up approach might possibly make use of artificial high-altitude atmospheric heating. This would create temporary bulges in the upper atmosphere, thus increasing drag on passing debris. Assuming the discovery of a controlled way to heat the atmosphere, this concept could offer a macroscopic and rapid method of eliminating essentially all debris in low orbits. Debris would experience rapid loss of energy leading to atmospheric reenter. Natural atmospheric drag does create orbital decay for objects in orbits of up to about 500 km, with decay times varying from a few months to a few decades. Artificial heating might be able to raise drag phenomena by several hundred kilometers.

V. Private and Commercial Aspects of Debris Reduction Solutions

While most people assume the space debris issue requires a government solution, there may be motivational incentives for addressing the debris removal challenge by other than the usual large government programs approach. Such incentives as awards for achievement or the potential for making a profit have proven to be strong motivators for innovation, dedication and determination. Here are two ideas for unconventional approaches to the debris removal challenge.

A. Incentives for the Private Sector

Surely, there are many formats for incentives that might spark a small group of innovators to create a cost-effective and safe debris reduction approach. One idea is the creation of something like the *X-Prize* for the best debris elimination ideas and demonstrations. An international government-sponsored and/or private sector organization sponsor might put up an award that is sufficiently large to attract several groups to a debris reduction competition. The objective might be the removal of a specific piece of debris or a given amount of debris. The original X-Prize award was $10 million for two suborbital flights. In a similar fashion the Google Lunar X-Prize is offering $20 million to the first privately-funded team to send a robot to the moon, travel 500 meters and transmit video, images and data back to Earth.[7] Since debris reduction requires complex mission scenarios, a debris removal prize might logically offer in excess of $20 million. At the very least such an incentive will raise awareness of space debris issues and provide a large public forum for more debris reduction solutions.

B. The Profit Motive

No agency of a space-faring nation will want to commit huge amounts of funding for the removal of space objects. National space agencies want to place satellites in orbit to satisfy productive objectives. Cleaning up orbits is not perceived as being productive. Almost certainly, civil servants and military personnel will not see this kind of mission as career enhancing, and very little enthusiastic support can be expected. Instead, consider the option of creating a private sector operation that is based on the profit motive. This requires an entrepreneur to write a convincing business plan that persuades the investment community to fund the project.

The first question asked will be: How can anyone make money with space debris? Space trash has little value compared to the tens or hundreds of millions of dollars needed to retrieve it. So, salvage does not seem to offer a viable business approach. However, an example of a possible private sector commercial venture might involve interactive gaming via the Internet. The idea is to create a *Space Debris Busters* game that could be accessible to most of the world's Internet-connected population. In theory, a private sector company could create a business plan that describes an international and interactive game to eliminate large space debris objects by using privately developed spacecraft and techniques to cause debris to be de-orbited through the actions of game players. Revenue could be created through dues and fees paid by gamers from all over the world. The concept could be set up to allow the players to challenge each other. Players could gain points by hitting debris pieces, with additional points for causing reentry. Those who accumulate a great deal of points could be awarded prizes.

Additional revenue might be possible through the creation of a worldwide lottery. Each debris piece that might possibly be de-orbited in a given week could be given a number. Lottery ticket buyers would guess which debris piece would reenter next. If no reentries occur in a given week, the lottery value increases each until there is a winner.

Since governments of space-faring nations would benefit by allowing a private-sector company to remove debris, it is likely that grants, low-interest loans or guarantees might be made available to assist in capitalizing the venture. Such assistance might be viewed as risky, but this approach avoids the otherwise inevitable taxing of every satellite launched to pay for debris clean up.

Assuming the business plan survives due diligence, consider operational concepts for such a system. One concept could involve the placement of a constellation of pellet-firing gun-satellites in orbits above the most dangerous debris altitudes. The system could be rigged such that all fired pellets would slow targeted debris such that they eventually reenter. These pellets could be ice spheres or even collected pieces of small debris that would be recycled in an effort to help eliminate other debris. Of course, all pellet firings would be controlled to avoid operational satellites. This description is oversimplified, but it describes the basic idea.

The key to success here is profitability. Based on recent private sector satellite constellation history, a cost estimate for development of the pellet-firing satellites, ground segment and system maintenance is in the five- to ten-billion-dollar range. Annual operating costs are estimated to be in the one-billion-dollar range. If ten million gamers each paid $150 per year to play, all expenses should be covered. The lottery could account for additional revenues. Amortization of the original investment might be recovered through a public offering. At first glance, the cost estimates may seem farfetched when compared to those of government systems. But, private sector entrepreneurs have demonstrated can made complex business models work effectively.

Although the space pellets approach may not be realistic, it is an example of what might be possible in the private sector. The video game industry took in almost $19 billion in 2007 in the U.S. alone.[8] The *Space Debris Busters* industry can be real and it is certainly exciting. With the right marketing, merchandizing and promotions programs, potential worldwide revenues might exceed those of video games.

There are a number of game variations. For example, it might be possible to make debris reduction into a spectator sport like tennis or golf. Two professional players could challenge each other to a game of debris chasing and removal. To further expand this business opportunity, it might be possible to create ancillary activities such as films based on space debris, television game shows in which contestants try to hit debris in real time and souvenir sales involving memorabilia.

At first glance this approach may seem far-fetched, but consider the many *reality* shows on television and how the movie studios merchandize film-related goods. It is often difficult to judge these entrepreneurial ideas until they are fleshed out and tested.

VI. Survey of Specific Debris Removal Methods

No one knows which solutions will eventually be adopted or succeed. At this point in the debris threat evolution the only logical discussion of possible debris reduction methods is some rational speculation about obvious and not-so-obvious options.

A. Small Debris Collection

The simplest approach to debris collection seems to be one that targets small debris pieces of sizes up to 10 cm. Due to the large number and small size of these debris objects, individual capture seems highly unlikely. Orbital maneuvering energies are far too excessive and costs are far too high for one-at-a-time rendezvous and retrieval operations. There are simply too many small pieces in too many different orbital planes that are not even being tracked. So, precise rendezvous for collection seems out of the question. This leaves only one apparent option, i.e., present large collisions cross sectional areas to small debris pieces in those orbital zones where operational satellites are most affected by potential collisions. Fortunately, these pieces should not need individual attention, because they generally carry relatively small amounts of momentum, thus permitting impact-capture or energy-reduction encounters with collector devices.

Small-debris-collection spacecraft will likely be configured as simple shapes with large frontal areas in order to maximize collision probabilities. These shapes could be spheres, large flat arrays or combinations of both. The underlying assumption here is that small debris will randomly collide with spacecraft having large frontal areas. Presumably, such vehicles can be designed to either slow or absorb the debris via a shielding material that is attached to the spacecraft. There are several materials and shapes that could be considered for debris collisions. For example, an aerogel material could be shaped into a sphere by inflating a folded bag once in orbit. A spherical shape may be best thought of as an uncontrolled *collision dummy* that has no preferred orientation. There are also planar shapes that may be effective, because they represent more cross sectional area than a sphere per unit mass. However, planar shapes would have to have orientation control to optimize effectiveness.

The term *uncontrolled* is used here to mean that collection satellites are not maneuvered to the debris. Instead, success requires debris to find the collection satellites. Every object that collides with the satellite will experience some loss of orbital energy. And, every time a debris object hits, there will be an energy exchange with the satellite: sometimes it will be an energy increase and sometimes an energy decrease. Accumulated energy changes will require these satellites to make occasional orbit adjustments. Additional maneuvers will ensure that large debris objects, such as expired spacecraft and operating satellites, are avoided. There may also be a required end-of-life maneuver to de-orbit collection satellites. However, this function often will not be necessary, because the combination of debris collisions, solar pressure and upper atmospheric drag could naturally lead to reentry.

Small debris collection methods using an *uncontrolled* approach as described above have unique implications. Even though only selected regions of space will require debris reduction, the volume to be addressed is huge. If we focus on the near-Earth space between the altitudes of 800 km and 1,100 km, the volume of that space is 202 billion cubic kilometers. Fortunately, we do not have to clear this entire volume, only enough to reduce the debris collision risks to acceptable levels. Even so, the collection process will require a large number of debris-collecting satellites. The actual number will be a function of urgency and collision cross section area on each vehicle. Assume an average orbital speed of 7.4 km/sec and a nominal collector diameter of 100 m. If 100 of these satellites are injected into circular retrograde orbits in the 300 km congested orbital band for 10 years, only about one percent of the volume would be swept. However, since most debris pieces are in posigrade orbits, the effective swept volume would be twice as much. Thus, heuristically, one can argue that 100 collector satellites can eliminate roughly 2% of the small debris objects every 10 years from this zone of high congestion. Based on the observed rate of debris growth and mitigation activities to limit new debris, a 20% reduction in small debris every 10 years may be sufficient to keep the risks to operational satellites in check. This can be done with 1,000 collector satellites of 100-meter diameter, each surviving for 10 years. The numbers of spacecraft and costs seem large, but the cost of not reducing debris seems much larger.

One positive observation is that large satellite production runs lead to lower unit costs. Such satellites would likely be launched in bunches on individual large launch vehicles. Similarly, large production runs for launch vehicles should lead to lower unit vehicle costs. In fact, there may be further cost savings for mission-dedicated launch vehicles through innovations in production processes and testing requirements. For example, expendable launchers that carry low-value payloads may not need the same level of hardware quality and reliability found in the current launch vehicle fleet. Lower reliability levels tend to reduce costs.[9]

Another launch option may come into play. The high frequency of satellites launches could create the needed incentive to develop an autonomous reusable launch vehicle (RLV) system. A great deal of progress was made in the decade from 1993 to 2003 toward the realization of two-stage-to-orbit RLVs. Such vehicles are considered to be beyond technological and economic reach. However, the underlying deterrent has been a lack of market demand. Once a mission is identified that requires a high launch frequency over a long timeframe for low-orbit payloads, enthusiasm for RLVs will build rapidly.

In addition to the orbital presence of small-debris collectors, there will certainly be a number of fully-controlled spacecraft to address large debris objects. These are addressed later.

B. Ground-Based Lasers

A number of recent studies have considered the feasibility of debris removal from low orbits through the use of high-powered lasers. One such approach suggests irradiating debris objects with a ground-based lasers, which would ablate a thin surface layer of the debris object and create a plasma consisting of neutral molecules, ions and electrons that are blown off. If this is repeated a sufficient number of times, it is possible to accumulate enough momentum exchange between the spacecraft and plasma blow off to lower the orbit of the debris until it naturally reenters. It is also possible to create momentum such that the orbit altitude is raised in order to remove debris from high-risk zones.

Another simple strategy calls for irradiating debris continuously during its passage through the laser's field of view. It must be noted that any strategy using lasers must incorporate safety with regard to overflying aircraft and operating satellites that may enter the laser's line of sight. In order to change the orbit of a debris piece, the desired momentum exchange should be oriented such that the object's speed is either decreased or increased in order to affect orbit decay or orbit raising, respectively. Thus, a logical strategy for orbit decay would call for laser engagement from a low angle above the horizon during ascending motion, until the object nears its zenith. In general, this approach will slow the object and cause some rotate of the velocity vector, both of which will contribute to encouraging the debris to reenter. Depending on the laser's power, debris size and orbit parameters, one or more engagements will be needed to induce reentry. Orbit raising is slightly more challenging, because a final parking orbit should be circular. This requires multiple laser engagements in all cases.

A few complex issues remain to be addressed. First, the use of lasers will likely be restricted to debris objects that can be precisely tracked and targeted. Current technology indicates that only large debris will qualify. Second, there is the issue of environmental effects of high-powered lasers burning through the atmosphere. Third, treaty issues regarding the use of space weapons will be debated, possibly for years. And, there are a myriad of other concerns including cost and benefit aspects of this approach versus other options, as well as technical challenges and operational details related to protocols and priorities. For example, a laser beam passing through the atmosphere will experience two detrimental phenomena, scintillation and non-linear effects.[10] Scintillation induces beam incoherence and spreading. Nonlinear effects cause beam spreading. Both of these tend to degrade laser performance and increase the difficulty of impacting the space debris population.

C. Trash Tenders and Attachable Devices

A method that has been suggested by many is to use a highly maneuverable satellite that can rendezvous with large debris objects.[11] In each case the debris would be captured and stowed for de-orbit later, or a retro-pack would be attached to effect individual reentry. In order to reach each targeted debris object the chasing satellite would have match the orbital speed and direction of the debris. Although this method is technically feasible it does require the use of large spacecraft with extremely large propellant loads in order to chase expired satellites and old upper stages. Mission operations must be optimized to make the best use of limited maneuvering. Nevertheless, each of these spacecraft will probably be limited to a very few debris objects between propellant resupplies. Thus, a fleet of chase vehicles will require a system for orbital servicing or frequent replacement. It is clear that this method will be expensive. However, the number of large objects to be removed from areas of high congestion in order to reduce risks are expected to be limited to a few hundred. These spacecraft might be referred to as *Space Trash Scows*, and they might incorporate highly efficient electric thrusters for maneuvering, a containment space for collected pieces and a number of attachable retro-pack devices. When debris reduction gets into full operation, there may be dozens of these spacecraft operating in high-traffic zones.

D. Dual-Use Orbit Transfer Vehicles

Another method is to use the trash tender as a "dual use" orbital transfer vehicle. Conceptually, this is a spacecraft that has two functions. They would deliver payloads to highly congested orbits and then collect debris during descent toward Earth. If these vehicles are reusable, they could rendezvous at low altitude with launch vehicles carrying replacement satellites, transfer the new satellites to higher orbits and then collect debris during return trips to low orbits. Debris would be ejected and left for reentry. If transfer vehicles are disposable, they might reenter with the debris still on board. A basic drawback would be restricted maneuverability after releasing a replacement satellite. It is likely that a very limited number of large debris pieces could be reached with limited propellant loads. Nevertheless, it may be worthwhile to investigate such possibilities. For example, Progress Modules that deliver supplies to the International Space Station might possible be capable of doing such a mission on an occasional basis. Some modification would be necessary, but this scheme might work in a limited number of cases.

This discussion logically leads to the question: Why not require every new orbiting spacecraft to not only de-orbit itself at the end of its life, but also to capture a large debris object during the process? There are obvious arguments on both sides of this question. Typically, these satellites cannot maneuver enough with the needed accuracy to capture any significant debris, especially at end-of-life. On the other side, it is the responsibility of every user of space to keep it accessible and safe for all users. If world governments ultimately have to solve the debris issue, there will inevitably be a "tax" laid on all space users to keep space flight safe from high levels of debris. As a possible incentive, this tax may be waived in those cases where satellites pick up debris on their way to reentry.

E. Space-Based Lasers

Lasers seem to offer an attractive option for debris reduction. Any serious consideration of their use must include the possible application of space-based laser-laden satellites. Putting these devices into orbit does offer a few unique advantages over ground-based systems. There are no negative atmospheric effects that might be of concern to environmentalists or to laser technologists. The lasers would presumably be able to track and target debris with a much larger field of view and focus on targets for longer periods of time. This could allow reduced power levels and a much larger selection of debris reduction options. However, there are a few issues that would be unique to space basing. The cost of building, launching and operating a fleet of laser satellites would be much higher than the ground-based option. There would undoubtedly be international opposition to establishing a space-based weapons system. In addition, there remain many complex technical and operational issues.

F. Space Tethers

Space tethers are generally thought of as long cables used to connect spacecraft to each other, or to other masses such as spent booster stages or large debris objects. Tethers that have been tested were made of thin strands of high-strength fibers or conducting wires. The purpose of a space tether is to provide a mechanical connection between two objects with which to transfer energy and/or momentum from one to the other. Experts claim that electrically conductive tethers can interact with the Earth's magnetic field and ionospheric plasma to generate thrust or drag without using onboard propellant. These devices have been proposed for many uses in addition to transferring energy and momentum between objects. For example, there are a number of claims that tether-based devices can: capture and release objects; be spin-stabilized; and cause orbit changes by using electrodynamic effects. In fact, tether devices have been proposed for space debris collection. In order to succeed, such devices would have to execute orbit and attitude changes, rendezvous and capture debris, change the orbits of debris and release debris objects such that they reenter the atmosphere or are left in graveyard orbits.

The underlying principle of the electrodynamic tether is the utilization of electromagnetic forces generated by a current passing through a long conductor in the earth's magnetic field. If currents are properly directed and timed, a net force can be generated that causes an orbit to change. According to electromagnetic theory, such a force is possible only in the presence of open-loop electric current flow. The space environment seems to offer the possibility. If tether researchers are correct, electrical current can flow along a tether and depart into the ambient plasma around the conductor. This has led to the conclusion that the Lorentz force acts only on the tether, creating a net force that may be used to make orbit adjustments.[12]

Although no physical principles appear to be violated, the use of tethers for debris reduction does introduce a number of engineering challenges. The Earth's magnetic field is essential to the electrodynamic tether concept, because it is the interaction of this field with the electrical current in tethers that creates net forces used to maneuver tether devices. The magnetic field varies in direction and magnitude with orbital position. Thus, a tether must continually adjust its orientation and the direction and level of current flow in order to carry out effective orbit changes. Since the tether must be stabilized and structurally stiff, it must be spinning. However, this further complicates operational aspects of debris collection. Nevertheless, the concept does seem to have some promise for debris removal applications. For example, there have been claims that such tethers can achieve velocity changes in excess of 50 km/sec/year for many years, without using propellant.[13]

VII. Conclusions

There are several fundamental realities about removing space debris. First and foremost, the debris issue presents near-term and long-term challenges. In the near term, there is an increasing critical need to address debris in low-Earth orbits. There is no need to eliminate all debris. The objective must be to reduce risks to operational spacecraft to levels that are acceptable to space-faring nations. This is an international problem and it will likely require an international effort to resolve it. Most space debris objects are resident in orbits below about 1,600 km, with peak densities between 800 km and 1,100 km. The U.S. Government can track objects that are at least 10 cm in size, but there are indications that there are at least hundreds of thousands of smaller debris pieces that cannot be tracked with any accuracy or consistency. Any debris removal program must divide operations into at least two modes: one for individual large object collection, and one for small debris elimination.

In the long term, debris control programs will have to address space debris accumulation in almost all orbits, from low to geostationary altitudes. There will be permanent debris control and orbit maintenance programs that will require special space systems to patrol and oversee near-Earth space. National and international debris advisory committees will evolve into regulatory bodies that will legislate and enforce debris proliferation issues. Debris clean up and maintenance operations must be funded through a taxation process, through entrepreneurial innovations or through some international multi-governmental programs.

The debris removal challenge will require the solution of many technical challenges, but the most difficult challenges will be political, legal, economic and cultural. No one in government wants to address debris removal, even though recent events clearly indicate this is an imperative. Human nature and political interests will likely try to put off a solution until catastrophic events increase in frequency. Even then, action may be slow in coming.

Only a few options and ideas have been included here. There is a myriad of innovations and potentially disruptive technologies just waiting for the moment that incentives are created to excite the many talented individuals and groups around the space world. Hopefully, this opportunity will not be delayed until corrective action becomes a great deal more expensive.

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